Study of Indium Tin Oxide (ITO) for Novel Optoelectronic Devices

by

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Submitted in accordance with the requirement for the Degree of Doctor of Philosophy

KING’S COLLEGE LONDON
University of London
Department of Electronic Engineering

1998
To,

My parents

and

in loving memory of my grandparents

“বিস্মিল্লাহ আর-রাহমান আর-রাহিম”

“যারা স্বনির্ভরতার পথ খোঁজে,
বুদ্ধি তাদেরকে সাহায্য করেন”
Acknowledgments

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Abstract

Indium Tin Oxide (ITO) films were deposited on a number of semi-conductor materials using reactive r.f. sputtering technique to form both rectifying Schottky and ohmic contacts. These contacts were applied in the fabrication of a number of novel optoelectronic devices: Schottky photo-diodes, transparent gate High Electron Mobility Transistors (HEMTs), heterojunction bipolar transistors (HBTs) being used as heterojunction phototransistors (HPTs), light emitting diodes (LEDs) and vertical cavity surface emitting lasers (VCSELs). A number of these novel devices were studied in comparatively greater detail; these were the Schottky diode and the HPT.

Deposition conditions necessary to produce ITO films with high conductivity and optical transparency over a wide spectral range were studied and optimised. Separate post deposition techniques were developed to produce near ideal rectifying contacts and ohmic contacts with low contact resistance respectively. A thin film of indium (In) was also used to optimise ITO ohmic contacts to n⁺ - GaAs substrates.

Near ideal Schottky diodes were realised on n-GaAs substrates using aluminium (Al) and gold (Au) metal contacts. A simulation model was then developed and implemented to study the behaviour of current transport mechanisms over a wide temperature range. Photodiodes with ITO as the Schottky metal contact were fabricated and a study comprising of both their electrical and optical behaviour was undertaken.

Relatively large geometry HBTs and HPTs were fabricated using AlGaAs/GaAs, InGaP/GaAs and InP/InGaAs systems respectively; the latter devices were first reported as a result of this study. A comparative study between devices fabricated from these systems were then made. This was followed by an appraisal of the electrical properties of each of their optical counterparts which had ITO emitter contacts. The specific photo responsivity and the spectral responses of these HPTs were analysed. In light of HPTs with transparent ITO emitter ohmic contacts, a brief examination of the merits of vertical versus lateral illumination was also made in this work.

Finally a spectral response model was developed to understand and help design optoelectronic detectors comprising of single layer devices (n-GaAs Schottky photo diodes) or multiple semiconductor materials (HPTs using AlGaAs/GaAs or InP/InGaAs systems) to help predict responsivities at a given incident wavelength. As well as material properties of the constituent semiconductors, this model takes into account the specific lateral and vertical geometrical dimensions of the device.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
<th>Units/Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Area</td>
<td>m²</td>
</tr>
<tr>
<td>α</td>
<td>Absorption co-efficient</td>
<td>cm⁻²</td>
</tr>
<tr>
<td>Å</td>
<td>Angstrom, unit of length (1Å = 10⁻¹⁰ m)</td>
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</tr>
<tr>
<td>A⁺</td>
<td>Richardson constant</td>
<td>Am⁻²K⁻²</td>
</tr>
<tr>
<td>A**</td>
<td>Modified Richardson constant</td>
<td>Am⁻²K⁻²</td>
</tr>
<tr>
<td>Al</td>
<td>Aluminium</td>
<td></td>
</tr>
<tr>
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<td>Argon</td>
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</tr>
<tr>
<td>As</td>
<td>Arsenic</td>
<td></td>
</tr>
<tr>
<td>Au</td>
<td>Gold</td>
<td></td>
</tr>
<tr>
<td>AuGe</td>
<td>Gold-germanium eutectic alloy</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Bandwidth</td>
<td></td>
</tr>
<tr>
<td>β</td>
<td>DC Current Gain of bipolar transistors</td>
<td></td>
</tr>
<tr>
<td>BER</td>
<td>Bit Error Rate</td>
<td></td>
</tr>
<tr>
<td>BJT</td>
<td>Bipolar Junction Transistor</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Capacitance</td>
<td>Farad, F</td>
</tr>
<tr>
<td>c</td>
<td>velocity of light in vacuum</td>
<td>3x10⁸ ms⁻¹</td>
</tr>
<tr>
<td>χₜ</td>
<td>Electron affinity of base</td>
<td>V</td>
</tr>
<tr>
<td>χₑ</td>
<td>Electron affinity of emitter</td>
<td>V</td>
</tr>
<tr>
<td>Cₚ</td>
<td>Correction factor</td>
<td></td>
</tr>
<tr>
<td>CH₄</td>
<td>Methane</td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
<td></td>
</tr>
<tr>
<td>χₛ</td>
<td>Electron affinity of a semiconductor</td>
<td>eV</td>
</tr>
<tr>
<td>CTO</td>
<td>Cadmium Tin Oxide</td>
<td></td>
</tr>
<tr>
<td>d</td>
<td>Film thickness (or MESA height in TLM analysis)</td>
<td>m</td>
</tr>
<tr>
<td>D</td>
<td>Diameter</td>
<td>m</td>
</tr>
<tr>
<td>δ</td>
<td>Thickness of oxide layer</td>
<td>m</td>
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<tr>
<td>ΔEₗ</td>
<td>Conduction band offset at a heterojunction in eV</td>
<td>eV</td>
</tr>
<tr>
<td>ΔE₉</td>
<td>Bandgap difference at a heterojunction in eV</td>
<td>eV</td>
</tr>
<tr>
<td>ΔEᵥ</td>
<td>Valence band offset at a heterojunction in eV</td>
<td>eV</td>
</tr>
<tr>
<td>Δφ</td>
<td>Image-force induced reduction to barrier height</td>
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<td>Dₙ</td>
<td>Electron diffusion constant</td>
<td>cm²s⁻¹</td>
</tr>
<tr>
<td>Dₚ</td>
<td>Hole diffusion constant</td>
<td>cm²s⁻¹</td>
</tr>
<tr>
<td>Dₛ</td>
<td>Density of surface states</td>
<td>cm⁻²</td>
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<tr>
<td>ΔVₑ0</td>
<td>Offset voltage</td>
<td>V</td>
</tr>
<tr>
<td>DVM</td>
<td>Digital Volt Meter</td>
<td></td>
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<td>Eₗbr</td>
<td>Breakdown electric field</td>
<td>Vm⁻¹</td>
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<td>Eₑ</td>
<td>Energy at the bottom of the conduction band in eV</td>
<td>eV</td>
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<tr>
<td>EDFA</td>
<td>Erbium Doped Fiber Amplifier</td>
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</tr>
<tr>
<td>Eₗf</td>
<td>Fermi level energy in eV</td>
<td>eV</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
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<tr>
<td>--------</td>
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<tr>
<td>$E_g$</td>
<td>Semiconductor bandgap in eV</td>
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<tr>
<td>$\varepsilon_0$</td>
<td>Permittivity of free space</td>
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<td>$E_0$</td>
<td>Tunneling constant</td>
<td></td>
</tr>
<tr>
<td>$E_{so}$</td>
<td>Tunneling parameter</td>
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</tr>
<tr>
<td>$\varepsilon_r$</td>
<td>Relative permittivity</td>
<td></td>
</tr>
<tr>
<td>$eV$</td>
<td>Electron volts, $(1eV = 1.602 \times 10^{-19} J)$</td>
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</tr>
<tr>
<td>$E_v$</td>
<td>Energy at the top of the valence band</td>
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<tr>
<td>$\Phi$</td>
<td>Photon flux</td>
<td></td>
</tr>
<tr>
<td>$\Phi_{abs}$</td>
<td>Photon flux absorbed in the semiconductor</td>
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</tr>
<tr>
<td>$\phi_b$</td>
<td>Barrier height</td>
<td></td>
</tr>
<tr>
<td>$\phi_{bo}$</td>
<td>Unbiased barrier height</td>
<td></td>
</tr>
<tr>
<td>FET</td>
<td>Field Effect Transistor</td>
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<tr>
<td>$\phi_m$</td>
<td>Work function of a metal</td>
<td></td>
</tr>
<tr>
<td>$\phi_h$</td>
<td>Barrier height to holes in the base-emitter junction</td>
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</tr>
<tr>
<td>$\phi_p$</td>
<td>Barrier height to electrons in the emitter-base junction</td>
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</tr>
<tr>
<td>$\Phi_{ref}$</td>
<td>Reflected photon flux</td>
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<tr>
<td>$\phi_s$</td>
<td>Work function of a semiconductor</td>
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</tr>
<tr>
<td>G</td>
<td>Optical gain</td>
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<tr>
<td>Ga</td>
<td>Gallium</td>
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<tr>
<td>GaAs</td>
<td>Gallium Arsenide</td>
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</tr>
<tr>
<td>Ge</td>
<td>Germanium</td>
<td></td>
</tr>
<tr>
<td>$g_m$</td>
<td>Transconductance of FETs</td>
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<td>$h$</td>
<td>Planck constant</td>
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<td>$\eta$</td>
<td>Quantum efficiency</td>
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<td>H$_2$O</td>
<td>Water</td>
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<td>Hydrogen Peroxide</td>
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<tr>
<td>H$_2$SO$_4$</td>
<td>Sulphuric acid</td>
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</tr>
<tr>
<td>H$_3$PO$_4$</td>
<td>Phosphoric acid</td>
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<tr>
<td>HBT</td>
<td>Heterojunction Bipolar Transistor</td>
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<tr>
<td>HCl</td>
<td>Hydrochloric acid</td>
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<tr>
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<td>High Electron Mobility Transistor</td>
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<tr>
<td>HF</td>
<td>Hydrofluoric acid</td>
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</tr>
<tr>
<td>$hv$</td>
<td>Photon energy</td>
<td></td>
</tr>
<tr>
<td>HPT</td>
<td>Heterojunction Photo Transistor</td>
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</tr>
<tr>
<td>I</td>
<td>Current</td>
<td></td>
</tr>
<tr>
<td>$I_b$</td>
<td>Base current (of a bipolar transistor)</td>
<td></td>
</tr>
<tr>
<td>$I_c$</td>
<td>Collector current (of a bipolar transistor)</td>
<td></td>
</tr>
<tr>
<td>$I_e$</td>
<td>Emitter current (of a bipolar transistor)</td>
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</tr>
<tr>
<td>$I_{gr}$</td>
<td>Current due to generation-recombination</td>
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<tr>
<td>$I_{lk}$</td>
<td>Leakage current</td>
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</tr>
<tr>
<td>In</td>
<td>Indium</td>
<td></td>
</tr>
<tr>
<td>$I_n$</td>
<td>Electron current</td>
<td></td>
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<tr>
<td>InGaAs</td>
<td>Indium Gallium Arsenide</td>
<td></td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Symbol(s)</td>
<td>Definition</td>
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<tr>
<td>--------------</td>
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<td>------------</td>
</tr>
<tr>
<td>InGaP</td>
<td></td>
<td>Indium Gallium Phosphide</td>
</tr>
<tr>
<td>InP</td>
<td></td>
<td>Indium Phosphide</td>
</tr>
<tr>
<td>I_p</td>
<td></td>
<td>Hole current A</td>
</tr>
<tr>
<td>I_ph</td>
<td></td>
<td>Photo current A</td>
</tr>
<tr>
<td>I_te</td>
<td></td>
<td>Current due to thermionic emission A</td>
</tr>
<tr>
<td>I tn</td>
<td></td>
<td>Current due to tunneling A</td>
</tr>
<tr>
<td>ITO</td>
<td></td>
<td>Indium Tin Oxide</td>
</tr>
<tr>
<td>J</td>
<td></td>
<td>Joule, unit of energy Acm$^{-2}$</td>
</tr>
<tr>
<td>J_n</td>
<td></td>
<td>Electron current density Acm$^{-2}$</td>
</tr>
<tr>
<td>J_p</td>
<td></td>
<td>Hole current density Acm$^{-2}$</td>
</tr>
<tr>
<td>k</td>
<td></td>
<td>Boltzmann constant 1.38 x 10$^{-23}$ JK$^{-1}$</td>
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<td>K</td>
<td></td>
<td>Kelvin, unit of absolute temperature</td>
</tr>
<tr>
<td>k'</td>
<td></td>
<td>Extinction co-efficient</td>
</tr>
<tr>
<td>kg</td>
<td></td>
<td>Kilogram, unit of mass</td>
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<tr>
<td>KOH</td>
<td></td>
<td>Potassium Hydroxide</td>
</tr>
<tr>
<td>λ</td>
<td></td>
<td>lamda, wavelength m</td>
</tr>
<tr>
<td>l</td>
<td></td>
<td>litre, unit of volume (1l = 10$^3$ cm$^3$)</td>
</tr>
<tr>
<td>L</td>
<td></td>
<td>Probe or pad spacing m</td>
</tr>
<tr>
<td>LED</td>
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<td>Light Emitting Diode</td>
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<tr>
<td>L_n</td>
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<td>Electron diffusion length m</td>
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<td>L_p</td>
<td></td>
<td>Hole diffusion length m</td>
</tr>
<tr>
<td>MBE</td>
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<td>Molecular Beam Epitaxy</td>
</tr>
<tr>
<td>m_e</td>
<td></td>
<td>mass of an electron kg</td>
</tr>
<tr>
<td>m_h</td>
<td></td>
<td>mass of a hole kg</td>
</tr>
<tr>
<td>H_H</td>
<td></td>
<td>Hall mobility cm$^2$V$^{-1}$s$^{-1}$</td>
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<tr>
<td>n_n</td>
<td></td>
<td>Electron mobility cm$^2$V$^{-1}$s$^{-1}$</td>
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<tr>
<td>MOCVD</td>
<td></td>
<td>Metalo-Organic Chemical Vapour Deposition</td>
</tr>
<tr>
<td>H_p</td>
<td></td>
<td>Hole mobility cm$^2$V$^{-1}$s$^{-1}$</td>
</tr>
<tr>
<td>ν</td>
<td></td>
<td>Oscillation frequency of electro-magnetic radiation Hz</td>
</tr>
<tr>
<td>n</td>
<td></td>
<td>Refractive index</td>
</tr>
<tr>
<td>N</td>
<td></td>
<td>Carrier concentration cm$^{-3}$</td>
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<tr>
<td>N_2</td>
<td></td>
<td>Nitrogen</td>
</tr>
<tr>
<td>N_A</td>
<td></td>
<td>Ionised acceptor concentration cm$^{-3}$</td>
</tr>
<tr>
<td>N_c</td>
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<td>Density of states in the conduction band cm$^{-3}$</td>
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<td>Critical doping density cm$^{-3}$</td>
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<td>Ammonia</td>
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<td>n_i</td>
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<td>Intrinsic carrier concentration cm$^{-3}$</td>
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<tr>
<td>Ni</td>
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<td>Nickel</td>
</tr>
<tr>
<td>n_no</td>
<td></td>
<td>Majority carrier concentration in n-type semiconductor cm$^{-3}$</td>
</tr>
<tr>
<td>n_po</td>
<td></td>
<td>Minority carrier concentration in p-type semiconductor cm$^{-3}$</td>
</tr>
<tr>
<td>N_v</td>
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<td>Density of states in the valence band cm$^{-3}$</td>
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<td>O_2</td>
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<td>Oxygen</td>
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<tr>
<td>π</td>
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<td>pi 3.141592654</td>
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<td>Abbreviation</td>
<td>Definition</td>
<td></td>
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<td>--------------</td>
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</tr>
<tr>
<td>P</td>
<td>Phosphorous</td>
<td></td>
</tr>
<tr>
<td>PAr</td>
<td>Partial pressure of argon</td>
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<tr>
<td>$p_{no}$</td>
<td>Minority carrier concentration in n-type semiconductor, $\text{cm}^{-3}$</td>
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<tr>
<td>$P_o$</td>
<td>Optical power, W</td>
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<tr>
<td>PO$_2$</td>
<td>Partial pressure of oxygen</td>
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<tr>
<td>$p_{po}$</td>
<td>Majority carrier concentration in p-type semiconductor, $\text{cm}^{-3}$</td>
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<tr>
<td>PT</td>
<td>Total Pressure, torr</td>
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</tr>
<tr>
<td>q</td>
<td>Charge on a proton, $1.6 \times 10^{-19}$ coulombs</td>
<td></td>
</tr>
<tr>
<td>r</td>
<td>Resistance, Ohms, $\Omega$</td>
<td></td>
</tr>
<tr>
<td>$\rho$</td>
<td>Resistivity, $\Omega \text{cm}$</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>Responsivity, $\text{AW}^{-1}$</td>
<td></td>
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<tr>
<td>$\rho_c$</td>
<td>Specific contact resistance, $\Omega \text{cm}^2$</td>
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<tr>
<td>$R_c$</td>
<td>Contact resistance, $\Omega$</td>
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<tr>
<td>$R_{cc'}$</td>
<td>Collector contact resistance, $\Omega$</td>
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<tr>
<td>$R_{Diode}$</td>
<td>Responsivity of diode, $\text{AW}^{-1}$</td>
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<td>$R_e$</td>
<td>End contact resistance, $\Omega$</td>
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<tr>
<td>$R_{ce'}$</td>
<td>Emitter contact resistance, $\Omega$</td>
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<td>$R_{HPT}$</td>
<td>Responsivity of HPT, $\text{AW}^{-1}$</td>
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<td>$R_{lk}$</td>
<td>Leakage resistor, $\Omega$</td>
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</tr>
<tr>
<td>$r_p$</td>
<td>Rate of photon arrival, s$^{-1}$</td>
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</tr>
<tr>
<td>$r_q$</td>
<td>Rate of photo-generated electron collection, s$^{-1}$</td>
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<tr>
<td>$R_s$</td>
<td>Series resistance, $\Omega$</td>
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</tr>
<tr>
<td>$R_{sh}$</td>
<td>Sheet resistance, $\Omega \text{□}$</td>
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</tr>
<tr>
<td>$R_{sk}$</td>
<td>Sheet resistance under an ohmic contact pad, $\Omega \text{□}$</td>
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<tr>
<td>RTA</td>
<td>Rapid Thermal Annealing</td>
<td></td>
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<tr>
<td>s</td>
<td>Length of a (TLM) contact pad, m</td>
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</tr>
<tr>
<td>SCR</td>
<td>Space Charge Region</td>
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<tr>
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<td>Silicon</td>
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<td>$S_{\lambda}$</td>
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<td>Tin</td>
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<td>SPA</td>
<td>Semiconductor Parameter Analyser (HP 4145B)</td>
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<tr>
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</tr>
<tr>
<td>TFA</td>
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<td></td>
</tr>
<tr>
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<td>Titanium</td>
<td></td>
</tr>
<tr>
<td>T$_{ITO}$</td>
<td>Optical transmittance of ITO film</td>
<td></td>
</tr>
<tr>
<td>$\tau_n$</td>
<td>Electron life time, s</td>
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</tr>
<tr>
<td>$\tau_p$</td>
<td>Hole life time, s</td>
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</tr>
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<tr>
<td>$V_{bc}$</td>
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</tr>
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<td>$V_{be}$</td>
<td>Base-emitter voltage, V</td>
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<tr>
<td>--------</td>
<td>------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>$V_{cc}$</td>
<td>Collector-emitter voltage</td>
<td>V</td>
</tr>
<tr>
<td>VCSEL</td>
<td>Vertical Cavity Surface Emitting Laser</td>
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<tr>
<td>$V_{eff}$</td>
<td>Effective bias across an interface</td>
<td>V</td>
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<td>Potential difference between $E_c$ and $E_f$</td>
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</tr>
<tr>
<td>$v_{nB}$</td>
<td>Mean electron velocity at the emitter end of the base</td>
<td>ms$^{-1}$</td>
</tr>
<tr>
<td>$V_p$</td>
<td>Potential difference between $E_f$ and $E_v$</td>
<td>V</td>
</tr>
<tr>
<td>$v_{pE}$</td>
<td>Mean hole velocity at the base end of the emitter</td>
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<tr>
<td>$V_r$</td>
<td>Reverse bias</td>
<td>V</td>
</tr>
<tr>
<td>$V_t$</td>
<td>Turn-on voltage (for a diode at a set current)</td>
<td>V</td>
</tr>
<tr>
<td>$W$</td>
<td>Watts, unit of power</td>
<td>W or Js$^{-1}$</td>
</tr>
<tr>
<td>$w$</td>
<td>Width of a (TLM) contact pad</td>
<td>m</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Angular frequency</td>
<td>radian s$^{-1}$</td>
</tr>
<tr>
<td>$w_b$</td>
<td>Base width (of a bipolar transistor)</td>
<td>m</td>
</tr>
<tr>
<td>$W_c$</td>
<td>Energy at the bottom of the conduction band</td>
<td>J</td>
</tr>
<tr>
<td>$W_f$</td>
<td>Fermi Level energy</td>
<td>J</td>
</tr>
<tr>
<td>$W_g$</td>
<td>Bandgap energy</td>
<td>J</td>
</tr>
<tr>
<td>$W_\lambda$</td>
<td>Spectral radiance</td>
<td>Wm$^{-2}$μm$^{-1}$</td>
</tr>
<tr>
<td>$W_v$</td>
<td>Energy at the top of the valence band</td>
<td>J</td>
</tr>
<tr>
<td>$x_{dep}$</td>
<td>Depletion width</td>
<td>m</td>
</tr>
<tr>
<td>$x_n$</td>
<td>Depletion width of n-type semiconductor</td>
<td>m</td>
</tr>
<tr>
<td>$x_p$</td>
<td>Depletion width of p-type semiconductor</td>
<td>m</td>
</tr>
<tr>
<td>Zn</td>
<td>Zinc</td>
<td></td>
</tr>
<tr>
<td>ZrB$_2$</td>
<td>Zirconium diboride</td>
<td></td>
</tr>
</tbody>
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2. Background Theory and Literature Review

2.1 Indium Tin Oxide (ITO)

Interest in transparent conductors can be traced back to 1907 when reports of transparent and conductive cadmium oxide (CdO) films first appeared. Since then there has been a growing technological interest in materials with these unique properties as evidenced by not only their increased numbers but also the large variety of techniques that have been developed for their deposition. It is now known that non-stoichiometric and doped films of oxides of tin, indium, cadmium, zinc and their various alloys exhibit high transmittance and nearly metallic conductivity is achievable [1]. However, tin doped indium oxide (ITO), with reported transmittance and conductivity as high as 95% and $10^4 \, \Omega^{-1}\text{cm}^{-1}$ respectively, is among the most popular of these thin films which have found a host of electronic, opto-electronic and mechanical applications. Hence, some of the physical and technological aspects behind ITO films will now be reviewed and discussed.

2.1.1 Introduction and Uses of ITO

Although partial transparency, with acceptable reduction in conductivity, can be obtained for very thin metallic films, high transparency and simultaneously high conductivity cannot be attained in intrinsic stoichiometric materials. The only way this can be achieved is by creating electron degeneracy in a wide bandgap ($E_g > 3\text{eV}$ or more for visible radiation) material by controllably introducing non-stoichiometry and/or appropriate dopants. These conditions can be conveniently met for ITO as well as a number of other materials previously mentioned.

Uses of ITO have traditionally ranged from transparent heating elements of aircraft and car windows, antistatic coatings over electronic instrument display panels, heat reflecting mirrors, antireflection coatings and even in high temperature gas sensors. Early electro-optic devices using ITO include CCD arrays, liquid crystal displays and as transparent electrodes for various display devices. More recently, ITO has been used as a transparent contact in advanced optoelectronic devices such as solar cells, light emitting and photo diodes, photo transistors and lasers - some for the first time as a result of this investigation [2]. Thus it is soon becoming an integral part of modern electronic technology wherever there is a potential for improving optical sensitivity of light detecting devices or quantum efficiency of light emitting devices.
However, with increased development in electronic technology has come the need for a greater understanding of the optical and electrical properties of ITO. As a result some of the solid state physics of ITO has also emerged. Although no concise and accurate knowledge is available, the literature survey indicates that many of these properties can be tailored by careful control of the deposition parameters.

### 2.1.2 Physical Structure and Properties of ITO

Indium Tin Oxide is essentially formed by substitutional doping of In$_2$O$_3$ with Sn which replaces the In$^{3+}$ atoms from the cubic bixbyte structure of indium oxide [3]. Sn thus forms an interstitial bond with oxygen and exists either as SnO or SnO$_2$ - accordingly it has a valency of +2 or +4 respectively. This valency state has a direct bearing on the ultimate conductivity of ITO. The lower valence state results in a net reduction in carrier concentration since a hole is created which acts as a trap and reduces conductivity. On the other hand, predominance of the SnO$_2$ state means Sn$^{4+}$ acts as a n-type donor releasing electrons to the conduction band. However, in ITO, both substitutional tin and oxygen vacancies contribute to the high conductivity and the material can be represented as $\text{In}_2x\text{Sn}_x\text{O}_{3.2x}$. ITO films have a lattice parameter close to that of In$_2$O$_3$ and lie in the range 10.12 to 10.31Å [4].

A summary of electrical and optical properties of typical ITO films deposited using various techniques is shown in Table 2.1. Variations in film properties can be easily noted; these are attributable to both pre- and post-deposition treatments as well as the techniques themselves.

<table>
<thead>
<tr>
<th>Deposition Technique</th>
<th>Thick [Å]</th>
<th>Hall Mobility $\mu_H$ [cm$^2$ V$^{-1}$ s$^{-1}$]</th>
<th>Carriers $N$ [cm$^{-3}$]</th>
<th>Resistivity $\rho$ [$\Omega$ cm]</th>
<th>Transmitt. $T_r$ [%]</th>
<th>Ref. No.</th>
</tr>
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<tr>
<td>r.f. Sputtering</td>
<td>7,000</td>
<td>35</td>
<td>$6 \times 10^{20}$</td>
<td>$3 \times 10^{-4}$</td>
<td>90</td>
<td>[5]</td>
</tr>
<tr>
<td>r.f. Sputtering</td>
<td>5,000</td>
<td>12</td>
<td>$12 \times 10^{20}$</td>
<td>$4 \times 10^{-4}$</td>
<td>95</td>
<td>[6]</td>
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<tr>
<td>r.f. Sputtering</td>
<td>4,000</td>
<td>25</td>
<td>$3 \times 10^{20}$</td>
<td>$8 \times 10^{-4}$</td>
<td>-</td>
<td>[7]</td>
</tr>
<tr>
<td>Magnetron Sputtering</td>
<td>800</td>
<td>26</td>
<td>$6 \times 10^{20}$</td>
<td>$4 \times 10^{-4}$</td>
<td>85</td>
<td>[8]</td>
</tr>
<tr>
<td>d.c. Sputtering</td>
<td>1,000</td>
<td>35</td>
<td>$9 \times 10^{20}$</td>
<td>$2 \times 10^{-4}$</td>
<td>85</td>
<td>[9]</td>
</tr>
<tr>
<td>Reactive Evaporation</td>
<td>2,500</td>
<td>30</td>
<td>$5 \times 10^{20}$</td>
<td>$4 \times 10^{-4}$</td>
<td>91</td>
<td>[10]</td>
</tr>
<tr>
<td>Ion Beam Sputtering</td>
<td>600</td>
<td>26</td>
<td>$2 \times 10^{20}$</td>
<td>$12 \times 10^{-4}$</td>
<td>-</td>
<td>[11]</td>
</tr>
<tr>
<td>Spray Pyrolysis</td>
<td>3,000</td>
<td>45</td>
<td>$5 \times 10^{20}$</td>
<td>$3 \times 10^{-4}$</td>
<td>85</td>
<td>[12]</td>
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</tbody>
</table>

Table 2.1: Typical electrical and optical properties of ITO deposited by various techniques
The high conductivity, $\sigma$, of ITO films is said to be due to high carrier concentration, $N$, rather than high Hall mobility, $\mu_H$ [1] bearing in mind that resistivity, $\rho = 1/\sigma = 1/(qN\mu_H)$ according to Ohm’s law. The observed low mobility of ITO, compared to bulk In$_2$O$_3$, and its dependence on carrier concentration and substrate temperature has been explained in terms of scattering mechanisms due to ionized impurities or grain boundaries. Mobility is said to increase due to enhanced crystallinity of films deposited at higher substrate temperatures [10]. TEM and electron diffraction studies of r.f. sputtered ITO films on glass substrates by Sreenivas et al suggest that films grown at room temperature have large stacking faults and represent an amorphous structure [6]; increasing this temperature to 200°C leads to a polycrystalline structure and finally annealing results in near single crystallinity with uniform grain size which leads to increased conductivity. The authors further suggest that deposition of ITO on single crystal substrates, rather than amorphous glass, can enhance the grain growth process.

The direct optical bandgap of ITO films is generally greater than 3.75 eV although a range of values from 3.5 to 4.06 eV have also been reported in the literature [3,13]. The high optical transmittance, $T_r$, of these films is a direct consequence of their being a wide bandgap semiconductor. The fundamental absorption edge generally lies in the ultraviolet of the solar spectrum and shifts to shorter wavelengths with increasing carrier concentration, $N$. This is because the bandgap exhibits an $N^{2/3}$ dependence due to the Moss-Burstein shift [14]. The band structure of ITO is assumed to be parabolic as shown in Figure 2.1:

![Figure 2.1: Assumed parabolic band structure of undoped In$_2$O$_3$ and the effect of tin doping; (After Gupta et al [14])](image-url)
The conduction band is curved upwards, the valence band is curved downwards and the Fermi level is located at mid bandgap for the undoped material; addition of Sn dopants results in the formation of donor states just below the conduction band. As the doping density is increased, these eventually merge with the conduction band at a critical density, \( n_c \), which was calculated to be \( 2.3 \times 10^{19} \text{ cm}^{-3} \) by Gupta et al. Free electron properties are exhibited by the material when the density of electrons from the donor atoms exceeds this value. As Table 2.1 shows, all reported values of carrier concentration are greater than \( n_c \). Hence all ITO films are expected to be degenerate in nature. Once the material becomes degenerate, the mutual exchange and coulombic interactions shift the conduction band downwards and the valence band upwards - effectively narrowing it from \( E_g \) to \( E_g' \) - as shown in Figure 2.1 earlier. The bandgap increase by the Burstein-Moss shift is partially compensated by this effect.

The reported value for the refractive index of ITO is 1.96. The transmittance of ITO films is also influenced by a number of minor effects which include surface roughness and optical inhomogeneity in the direction normal to the film surface. Inadvertently grown dark brown (effectively translucent) metallic films of ITO have also been reported. This opaqueness has been attributed to unoxidised Sn metal grains on the ITO surface as a result of instability due to absence of sufficient oxygen during deposition.

2.1.3 ITO Deposition Techniques

Sputtering, of one form or another, is by far the most extensively used technique for the deposition of ITO. This is closely followed by thermal evaporation - which can also be achieved using several different techniques. ITO has also been prepared by other methods such as Spray Pyrolysis and Screen Printing. The choice of deposition technique is dictated by a number of factors such as quality and reproducibility of the ITO film, homogeneity over a wide cross section, capacity, ease and cost of use as well as detrimental side effects and limitations specific to each technique. In addition, since the properties of ITO depend strongly on the microstructure, stoichiometry and the nature of the impurities present, it is inevitable that each deposition technique with its associated controlling parameters should yield films with different characteristics. Some of these issues will now be discussed briefly.

2.1.3.1 Sputtering

Sputtering involves knocking an atom or molecule out of a target material by accelerated ions from an excited plasma and condensing it on the substrate either in its original or in a
modified form. When this modification is induced by a chemical reaction during the transit from the target to the substrate, the process is referred to as reactive sputtering. In general, most ITO sputter sources consist of hot pressed 90% In$_2$O$_3$ : 10% SnO$_2$ compound targets. The sputtering can be achieved by a number of ways which include accelerating the plasma ions by a d.c. field [9] or a d.c. field combined with a magnet (to direct the high velocity emitted electrons away from the substrate), r. f. (with its self induced bias) as well as by ion beams [11]. Hence names such as magentron [8] and reactive r.f. sputtering [5,6] reflect on the process that has been used for the deposition of the ITO film.

The technique used in the course of this study involves reactive r. f. sputtering in an Ar/O$_2$ plasma. This method is reputed for its excellent uniformity, high conductivity and high transparency. The r. f. field ensures that sputtering of non-conductive materials can also be achieved at a practical rate. Parameters known to influence ITO quality include sputtering pressure, pre-conditioning, film thickness and r. f. power amongst others. The control of oxygen partial pressure is particularly critical in determining the conductivity and transmittance. However, without the ability to direct unwanted high velocity electrons away from the substrate, damage is associated with this technique; on the other hand magentron sputtering yields high deposition rates and minimises this damage. Detailed description of the system used here is presented in section 3.2 while the detailed optimisation of the deposition parameters is discussed in section 5.1 and elsewhere in the thesis.

2.1.3.2 Thermal Evaporation

Thermal evaporation involves vaporising a solid by heating the material to sufficiently high temperatures and recondensing it on a cooler substrate. The high temperature can be achieved by resistively heating or by firing an electron or ion beam at the boat containing the material to be evaporated. Similarly, reactive thermal evaporation is achieved by introducing oxygen into the chamber during deposition and is one of the most widely and successfully used techniques for good quality ITO depositions [10]. A 95% In - 5% Sn alloy (by weight) is commonly used as the source.

There is no damage associated with resistive thermal evaporation since there are no high velocity particles. Film properties strongly depend on oxygen partial pressure and film thickness [15], deposition rate, substrate temperature and tin concentration [13]. Reports of substrate temperatures being raised from 300°C up to 450°C during evaporation in order to enhance conductivity and transmittance are available in the literature [16].
2.1.3.3 Spray Pyrolysis Technique

Pyrolysis refers to the thermal decomposition of gaseous species at a hot susceptor surface. The spray deposition scheme is particularly attractive because of its relatively fast rate (> 1000 Å/sec) and because it does not require a vacuum. The ITO spray is obtained from an alcoholic solution of anhydrous indium chloride (InCl$_3$) and tin chloride (SnCl$_4$.5H$_2$O) with nitrogen acting as the carrier gas. The spraying is carried out in a furnace, held at 400°C. Critical parameters including positioning of the substrate and the chemical composition of the spray solution. Ashok et al [17] have reported resistivities of $1 \times 10^{-3}$ Ωcm for a 4200 Å thick ITO film with transmission greater than 90% at 550 nm while corresponding values obtained by Haitjema et al are $3 \times 10^{-4}$ Ωcm and 85% respectively [12]. As for most other techniques, this demonstrates an apparent trade-off between the conductivity and the transmittance of ITO films.

2.1.3.4 Screen Printing Technique

This technique is suitable for large scale non-device orientated applications where relatively thick layers of ITO are required such as in liquid crystal displays, blackwall contacts and anti reflection coatings for solar cells [18]. Typically, the deposited thickness varies in the range 10 to 30 µm and the post deposition crystallization temperature can be as high as 600°C for a period exceeding an hour. Although the resistivity (> $4 \times 10^{-4}$ Ωcm) of the ITO film is said to be comparable to those obtained by other deposition techniques, its transparency is markedly lower (< 80%).

2.2 Schottky Contacts

Although our knowledge of Metal-Semiconductor contacts can be traced as far back as early work by Braun (1874), it was not until 1938 that both Schottky and Mott independently suggested a model for the rectification mechanism. They pointed out that the observed direction of rectification could be explained by supposing that electrons passed over a potential barrier through the normal process of drift and diffusion.
2.2.1 Theory of Rectifying Metal Semiconductor Contacts

The basic theory of these contacts is outlined in the following material. A more comprehensive version was recently reviewed by Rhoderick [19,20]. Figure 2.2 shows a schematic of the band structure of an unbiased metal semiconductor contact.

The Schottky-Mott theory is expressed as follows:

\[ \phi_{bo} = \phi_m - \chi_s \]  \hspace{1cm} (eqn. 2.1)

where,

- \( \phi_{bo} \) = contact barrier height, at zero applied bias
- \( \phi_m \) = work function of the metal
- \( \chi_s \) = electron affinity of the semiconductor and is further expressed:

\[ \chi_s = \phi_s - (E_c - E_f) \]  \hspace{1cm} (eqn. 2.2)

where,

- \( \phi_s \) = work function of the semiconductor
- \( E_c \) = conduction band energy, in eV
- \( E_f \) = Fermi energy level, in eV

Figure 2.2: Unbiased band structure of a metal/n-type semiconductor contact

\( \phi_{bo} \) is the barrier encountered by electrons in the metal whereas the built-in potential, \( V_{bi} \), encountered by electrons in the semiconductor, is given by:

Here, \( V_{app} = 0 \)
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\[ V_{bi} = \phi_m - \phi_s \]
\[ = \phi_{bo} - (E_c - E_F) \]  
(eqn. 2.3)

This theory is rather simplistic in the sense that it assumes ideal conditions where dipole surface contributions to the barrier height and the electron affinity are thought to be unchanged when the metal and the semiconductor are brought into contact. It also assumes that there are no chemical reactions or physical strains created between the two when they are brought into contact.

In practice, however, surface dipole layers do arise. This is because at the surface of a solid the atoms have neighbours on one side only. This causes a distortion of the electron cloud belonging to the surface atoms, so that the centres of the positive and negative charge do not coincide. It was discovered that \( \phi_{bo} \) does not depend on \( \phi_m \) in contradiction to (eqn. 2.1). Thus the assumption of constancy of the surface dipole cannot be justified.

One of the first explanations for the departure of experiment from this theory was given in terms of localised surface states or “dangling bonds”. The surface states are continuously distributed in energy within the forbidden gap and are characterised by a neutral level, \( \phi_0 \), such that if the surface states are occupied up to \( \phi_0 \) and empty above \( \phi_0 \), the surface is electrically neutral.

In general, the Fermi level does not coincide with the neutral level. In this case, there will be a net charge in the surface states. If, in addition (and often in practice due to chemical cleaning of the semiconductor prior to processing) there is a thin oxide layer between the metal and the semiconductor the charge in the surface states together with its image charge on the surface of the metal will form a dipole layer. This dipole layer will alter the potential difference between the semiconductor and the metal. Thus the modification to the Schottky-Mott theory is expressed as follows [19]:

\[ \phi_{bo} = \gamma(\phi_m - \chi_s) + (1 - \gamma)(E_g - \phi_0) \]  
(eqn. 2.4)

where,

\[ E_g = \text{bandgap of the semiconductor, in eV} \]
\[ \phi_0 = \text{position of neutral level (measured from the top of the valence band)} \]

and,

\[ \gamma = \frac{\varepsilon_i}{\varepsilon_i + q\delta D_s} \]  
(eqn. 2.5)
where,
\[
\varepsilon_i = \text{permittivity of oxide layer} \\
\delta = \text{thickness of oxide layer} \\
D_s = \text{density of surface states}
\]

Hence if there are no surface states, \(D_s = 0\) and \(\gamma = 1\) and (eqn. 2.4) becomes identical to (eqn. 2.1) (the original Schottky-Mott approximation). But if the density of states is very high, \(\gamma\) becomes very small and \(\phi_{bo}\) approaches the value \((E_g - \phi_o)\). This is because a very small deviation from the Fermi level from the neutral level can produce a large dipole moment, which stabilises the barrier height by a negative feedback effect [19,20]. When this occurs, the Fermi level is said to be “pinned” relative to the band edges by the surface states.

### 2.2.2 Current transport mechanisms in the Schottky diode

The current transport through the device by emission over the barrier is essentially a two step process: first, the electrons have to be transported through the depletion region, and this is determined by the usual mechanisms of diffusion and drift; secondly, they must undergo emission over the barrier into the metal, and this is controlled by the number of electrons that impinge on unit area of the metal per second. This is expressed in (eqn. 2.6):

\[
I = A A** T^2 \cdot \exp\left(-\frac{q \phi_{bo}}{kT}\right) \cdot \exp\left(\frac{V_{\text{eff}}}{nkT}\right) - 1
\]

(eqn. 2.6)

where,
\[
A = \text{cross-sectional area of the metal/semiconductor interface} \\
A** = \text{Modified Richardson constant for metal/semiconductor interface} \\
T = \text{temperature in kelvins} \\
k = \text{Boltzmann constant} \\
q = \text{electronic charge} \\
V_{\text{eff}} = \text{effective bias across the interface} \\
n = \text{ideality factor}
\]

The ideality factor, \(n\), in (eqn. 2.6) gives a measure of the quality of the junction which is highly process dependent. For an ideal Schottky junction, \(n = 1\). In practice, however, larger values are obtained due to the presence of non-ideal effects or components to the current through the junction. This mode of current transport is commonly referred to as the “thermionic emission” current [21,22].
where,

\[ I_{gro} = \text{generation-recombination saturation current and is given by:} \]

\[ I_{gro} = \frac{q n_i x_{dep} A}{2 \tau_o} \]  \hspace{1cm} (eqn. 2.9)

where,

\[ n_i = \text{intrinsic carrier concentration of the semiconductor} \]
\[ x_{dep} = \text{depletion width} \]
\[ \tau_o = \text{effective carrier lifetime within the depletion width} \]

2.2.2.4 Current due to Quantum Mechanical Tunneling

For a moderately to heavily doped semiconductor or for operation at low temperatures, the current due to quantum mechanical tunneling of carriers through the barrier may become the dominant transport process [21, 24]. For all except very low biases, the tunneling current, \( I_{tn} \), can be represented by:

\[ I_{tn} = I_{tno} \exp \left( \frac{q V_{app}}{E_o} \right) - 1 \]  \hspace{1cm} (eqn. 2.10)

where,

\[ I_{tno} = \text{tunneling saturation current.} \]
\[ E_o = \text{tunneling constant} \]

The tunneling saturation current is a complicated function of temperature, barrier height and semiconductor parameters. In the notation of Padovani and Stratton [21], \( E_o \) is given by:

\[ E_o = E_{oo} \coth \left( \frac{E_{oo}}{kT} \right) \]  \hspace{1cm} (eqn. 2.11)

where,

\[ E_{oo} = \text{a tunneling parameter inherently related to material properties of the semiconductor and is expressed as:} \]

\[ E_{oo} = \frac{q h}{4 \pi} \sqrt{\frac{N_D}{m_n^* \varepsilon_0 \varepsilon_r}} \]  \hspace{1cm} (eqn. 2.12)
where,
\[ h = \text{Planck's constant} \]
\[ N_D = \text{impurity doping concentration} \]
\[ m_n^* = \text{effective mass of electron} \]

### 2.2.2.5 Leakage Current

The leakage current, \( I_{lk} \), is another parallel component of the total current. It is caused by surface leakage and can usually be significantly reduced by various designs and fabrication techniques. In practice, it is the component which appears to by-pass the metal/semiconductor interface altogether and is often thought of as a large leakage resistor, \( R_{lk} \), in parallel to it. Thus the leakage current can be expressed as:

\[
I_{lk} = \frac{V_{app}}{R_{lk}} \tag{eqn. 2.13}
\]

### 2.3 Ohmic Contacts

The term “ohmic” refers in principle to a (metal-semiconductor) contact which is non-injecting and has a linear I-V characteristic in both directions. In practice the contact is usually acceptable if it can supply the required current density with a voltage drop that is very small compared to the drop across the active region of the device even though it’s behaviour may not be strictly linear.

Historically, metal-semiconductor contacts were predominantly used as rectifying contacts until suitable methods of fabricating p-n junctions became available. Then, these contacts began to assume a less significant role as ohmic contacts for transporting current into and out of p-n junctions. With greater understanding and technological advancements, there was a renaissance of the rectifying metal-semiconductor or Schottky contact in the 1960’s. At the same time, the need for higher speed devices with their smaller and more complex geometries acted as the driving force behind the search for high performance ohmic contacts.
2.3.1 Theory of Ohmic Contacts

One of the most comprehensive papers that deals with the theory of ohmic contacts to III-V compound semiconductors is that by Rideout [25]. Nearly all practical metal-semiconductor contacts initially result in the formation of depletion layer Schottky barriers as shown in Figure 2.3. As such, they are essentially rectifying to begin with.

![Figure 2.3: Schematic band energy diagram of a metal/n-semiconductor contact showing the three major current transport mechanisms: thermionic emission (TE), thermionic-field emission (TFE) and field-emission (FE).](image)

The conduction properties of these contacts are determined by the actual transport mechanisms, most of which were discussed in section 2.2:

- TE - thermionic emission of carrier, giving rise to rectifying behaviour
- TFE - thermionic field emission or tunneling of hot carriers through the top of the barrier
- FE - field emission or carrier tunneling through the entire barrier (the preferred mode in ohmic contacts)

In addition to these, recombination in the depletion region and the lowering of the barrier due to image force also affect, albeit to a much lesser extent, the behaviour of the ohmic contact. Taking the expressions for the first three dominant mechanisms, the current is determined by [26]:

$$\exp \frac{\phi_b}{kT} \quad \text{for TE} \quad \text{(eqn. 2.14)}$$
exp \left[ \frac{\phi_b}{E_{oo} \coth \left( E_{oo}/kT \right)} \right] \quad \text{for TFE} \quad \text{(eqn. 2.15)}

\exp \left[ \frac{\phi_b}{E_{oo}} \right] \quad \text{for FE} \quad \text{(eqn. 2.16)}

where $E_{oo}$ is the tunneling parameter proportional to $\sqrt{N_d}$ (the doping concentration).

Thus, for $kT/E_{oo} \gg 1$, TE dominates and the contact is rectifying; for $kT/E_{oo} \ll 1$, FE dominates and the contact is ohmic while a mixed mode prevails for the condition $kT/E_{oo} \approx 1$. Note that both TE and TFE are temperature dependent while FE is not.

It is seen that there are several possible ways of achieving a good ohmic contact:

- The most common method is to have a layer of very highly doped semiconductor (typically $N_D = 5 \times 10^{18}$ cm$^{-3}$ for n-type GaAs) immediately adjacent to the metal giving rise to a very narrow depletion/barrier width ($\approx 100\,\text{Å}$). Increased conduction is then dominated by quantum mechanical tunneling.

- Another approach is to have a negligible potential barrier, $\phi_b$, to start with. In practice, this is harder to achieve for III-V covalent compounds such as GaAs where $\phi_b$ is essentially determined by interface states rather than the difference between the work function of the metal and the electron affinity of the semiconductor as theory predicts.

- A third approach is to deliberately increase interface states aimed at reducing contact resistance by causing space-charge recombination to dominate. But, in practice, this has adverse effects on the device stability.

2.3.2 Practical Ohmic contacts

In most practical ohmic contacts the metal layers usually contain a suitable dopant species - donor or acceptor atoms. A heat treatment is used to drive the dopant into the semiconductor to form a n$^{++}$ or p$^{++}$ layer thus creating a tunneling metal-semiconductor junction required for enhanced ohmic behaviour. The quality of an ohmic contact is ultimately assessed by determining its specific contact resistance, $\rho_c$, as discussed later in section 4.1.

Other desirable properties of ohmic contacts include good adhesion to the semiconductor, smooth surface morphology (particularly where near micron device geometry is concerned), ability to bond gold wires to connect the device to external circuitry and finally contact
reliability. With these in mind, the practical ohmic contact system often consists of a “wetting agent” to promote adhesion, followed by the dopant species and finally a thick layer of Au for bonding purposes. Where indiffusion of the top Au poses potential reliability hazards, often a diffusion barrier is inserted between the gold and the dopant layer.

The most commonly used n-type contacts to GaAs is the Ni/AuGe/Ni/Au system. Thus many studies have been carried out to determine its alloying behaviour [27], effect of varying Ge (the dopant species) content [28] as well as investigation of the semiconductor surface cleanliness prior to metalisation [29]. However, this system has several ill effects such as “balling up” during annealing as a result of liquid phase reactions, non-uniform contact resistivity and vertical and lateral spiking. An alternative which addresses many of these issues is the Pd/Ge/Au system [30,31].

The usual p-type contact for GaAs is the Au/Zn/Au system [32] where Zn atoms act as acceptors. In devices such as HBTs base is very thin (>1000Å); hence junction shorting due to Au spiking is often more of a concern than the resistivity, especially for high temperature or high current applications. In this case, Pt/Ti/Au is used as an alternative [33] although there are no dopant species. It is argued that since the base doping is already very high (N_A > 5x10^19 cm^-3) the need for extra acceptor atoms is diminished.

Pd/Ge based systems are known to have been used as both n and p-type contacts to InGaAs layers [34]. As in p-GaAs, Zn atoms also act as acceptors in p-InGaAs [35].

### 2.4 Heterojunction Bipolar Transistors

The idea behind the heterojunction bipolar transistor (HBT) is as old as the transistor itself. It was proposed by W. Shockley in 1948 and subsequently patented by him in 1951 [36]. However it was H. Kromer [37], who is credited with developing the detailed theory and analysis of HBTs leading up to its present day status in semiconductor electronics and integrated circuit applications.

#### 2.4.1 Heterostructure Concepts

Kromer’s Central Design Principle (CDH) of heterostructure devices uses the energy gap variations in addition to electric fields as forces acting on electrons and holes, to control their distribution and flow [38]. Therefore, by carefully selecting the appropriate bandgap and the
electric fields, it becomes possible (within limits) to control the forces acting on electrons and holes, *separately and independently of each other* - a design freedom not rendered by homostructures. With the evolution of more and more advanced growth technologies such as MBE and MOCVD, a change in semiconductor (and hence in energy gap) is not significantly harder to achieve than a change in doping level.

In a practical HBT, the emitter consists of a wide bandgap material (e.g. AlGaAs, InGaP or InP) while the base is a narrow bandgap material (e.g. GaAs or InGaAs). The band energy diagram for such an emitter-base heterojunction, before and after the two materials are brought into contact, is depicted in Figure 2.4a and b respectively.

![Energy band diagram](image)

Figure 2.4: Energy band diagram of a wide bandgap N-type emitter and a narrow bandgap p-type base heterojunction at equilibrium (a) before and (b) after formation.

As in homojunctions, once contact is made the conduction and valence bands join in a manner such that the Fermi levels align. However, since the electron affinities of the emitter and the base, $\chi_E$ and $\chi_B$ respectively, are different in heterojunctions a discontinuity in the conduction band, $\Delta E_c$, appears. Analytically, this is given by:

$$\Delta E_c = \chi_B - \chi_E$$  \hspace{1cm} (eqn. 2.17)

Since, the bandgap energies are different, a discontinuity in the valence band, $\Delta E_v$, also appears. The total bandgap discontinuity, $\Delta E_g$, is the sum of the discontinuities in the conduction and valence bands:
\[ \Delta E_g = \Delta E_c + \Delta E_v \]  
(eqn. 2.18)

In the HBT a large \( \Delta E_c \) is undesirable as it acts as an extra barrier to electron injection from the emitter to the base thereby requiring a high emitter-base forward bias voltage, \( V_{be} \), (typically 1.3V) [39]. This ultimately limits the device current gain far below that expected from an HBT [38]. By the same analogy, a large \( \Delta E_v \) is ideal as it limits reverse injection of holes from the base into the emitter. Table 2.2 lists some of the band discontinuities of common HBT systems. Thus a large \( \Delta E_v / \Delta E_c \) ratio is desirable.

<table>
<thead>
<tr>
<th>HBT Material Structure</th>
<th>( \Delta E_c ) (eV)</th>
<th>( \Delta E_v ) (eV)</th>
<th>( \Delta E_g ) (eV)</th>
<th>( \Delta E_v / \Delta E_c )</th>
<th>Ref. no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Al}<em>{0.3}\text{Ga}</em>{0.7}\text{As/GaAs} )</td>
<td>0.24</td>
<td>0.13</td>
<td>0.37</td>
<td>0.54</td>
<td>[40]</td>
</tr>
<tr>
<td>( \text{In}<em>{0.5}\text{Ga}</em>{0.5}\text{P/GaAs} )</td>
<td>0.19</td>
<td>0.29</td>
<td>0.48</td>
<td>1.53</td>
<td>[41, 42, 43]</td>
</tr>
<tr>
<td>( \text{InP/In}<em>{0.53}\text{Ga}</em>{0.47}\text{As} )</td>
<td>0.25</td>
<td>0.34</td>
<td>0.59</td>
<td>1.36</td>
<td>[44]</td>
</tr>
</tbody>
</table>

Table 2.2: Band discontinuities for common HBT material heterostructures

Heterojunctions, such as InGaP/GaAs which naturally exhibit relatively large \( \Delta E_v \) compared to their \( \Delta E_c \), are more advantageous than AlGaAs/GaAs. However, since AlGaAs is lattice matched to GaAs for all fractions of Al, it is possible to reduce or even remove this conduction band discontinuity by compositionally grading the mole fraction of Al in the emitter material immediately (few hundred angstroms) before the GaAs base [45]. This helps lower the \( V_{be} \) by 150mV compared to that in the non-composition graded emitter HBTs. However, it should be noted that the bandgap of AlGaAs becomes indirect once the Al mole fraction is raised above 50%, and thus is not of interest from a device application point of view.

Using Figure 2.4 the built-in potential, \( V_{bi} \), for a heterostructure can be derived as follows:

\[ E_{gE} - V_n = \Delta E_v + V_p + V_{bi} \]  
(eqn. 2.19)

where,
- \( E_{gE} \) = emitter bandgap in eV
- \( V_n \) = potential difference between the bottom of conduction band and Fermi level
- \( V_p \) = potential difference between Fermi level and the top of valence band
Expressing $V_n$ and $V_p$ in terms of emitter and base doping levels, $N_{DE}$ and $N_{AB}$, and the respective density of states in emitter conduction band and base valence band, $N_{cE}$ and $N_{vB}$, we obtain:

\[
V_n = (E_{cE} - E_{fE}) = -\frac{kT}{q} \ln \left( \frac{N_{DE}}{N_{cE}} \right) \tag{eqn. 2.20}
\]

and,

\[
V_p = (E_{fB} - E_{vB}) = -\frac{kT}{q} \ln \left( \frac{N_{AB}}{N_{vB}} \right) \tag{eqn. 2.21}
\]

Combining (eqn. 2.18) to (eqn. 2.21), we obtain:

\[
V_{bi} = E_{gE} + \frac{kT}{q} \ln \left( \frac{N_{DE}}{N_{cE}} \right) - \Delta E_g + \Delta E_c + \frac{kT}{q} \ln \left( \frac{N_{AB}}{N_{vB}} \right) \tag{eqn. 2.22}
\]

But,

\[
\Delta E_g = E_{gE} - E_{gB} \tag{eqn. 2.23}
\]

Hence,

\[
V_{bi} = E_{gB} + \Delta E_c + \frac{kT}{q} \ln \left( \frac{N_{DE} N_{AB}}{N_{cE} N_{vB}} \right) \tag{eqn. 2.24}
\]

2.4.2 Current Transport in HBTs

The operating principle of a (n-p-n) bipolar transistor consists of electron injection from the emitter into the base and their subsequent collection by the collector. Figure 2.5 shows the energy band structure of an N-p-n HBT with wide-gap emitter, with the various current components, and the hole repelling effect of the additional energy gap in the emitter. The band energies are expressed in joules; thus bandgap is expressed using $W_g$ rather than $E_g$. In this case it is assumed that the emitter junction has been graded sufficiently to obliterate any band edge discontinuities or even any non-monotonic variations of the conduction band edge.
There are the following injection related dc currents flowing in such a transistor:

1. A current $I_n$ of electrons injected from the emitter into the base;
2. A current $I_p$ of holes injected from the base into the emitter;
3. A current $I_{scr}$ due to electron-hole recombination within the forward biased emitter-base space-charge layer.
4. A small part, $I_{bulk}$, of the electron injection current, $I_n$, is lost due to bulk recombination in the base.
5. A small thermally generated minority hole current from the n-type collector, $I_{cbo}$, flows into the base from the reverse biased base-collector junction.

Emitter current, \[ I_e = I_n + I_p + I_{scr} \]  \hspace{1cm} (eqn. 2.25)

Collector Current, \[ I_c = I_n - I_{bulk} + I_{cbo} \]  \hspace{1cm} (eqn. 2.26)

Base Current, \[ I_b = I_p + I_{bulk} + I_{scr} - I_{cbo} \]  \hspace{1cm} (eqn. 2.27)

The device operation mainly depends on current contribution $I_n$ while the other components are strictly nuisance currents, as are capacitive currents (not shown above) that accompany voltage changes. The effect of the space charge recombination current, $I_{scr}$, on the transistor
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Performance has been explained elsewhere by Morgan et al [46]. Since the base thickness, \( w_b \), is much smaller than the electron diffusion length, \( L_{nB} \), in the base, \( I_{\text{bulk}} \) is very small. Similarly, any currents due to electron-hole pair generation in the collector depletion layer, \( I_{\text{cebo}} \), are also insignificant and can be ignored at this stage. Expressed in terms of the dc current gain, \( \beta \):

\[
\beta = \frac{I_c}{I_b} = \frac{I_n - I_{\text{bulk}} + I_{\text{cebo}}}{I_p + I_{\text{bulk}} + I_{\text{scr}} - I_{\text{cebo}}}
\]

(eqn. 2.28)

and,

\[
\beta_{\text{max}} = \frac{I_n}{I_p + I_{\text{scr}}}
\]

(eqn. 2.29)

\( \beta_{\text{max}} \) is the highest possible value of \( \beta \) in the limit of various negligible recombination and other minor currents; in fact, it is the improvement in \( \beta_{\text{max}} \) to which the wide-gap emitter idea addresses itself. This can be expressed in terms of the electron and hole injection current densities, \( J_n \) and \( J_p \) [38]:

\[
J_n = N_{DnB} v_{nB} \exp \left( -\frac{q\phi_n}{kT} \right)
\]

(eqn. 2.30)

\[
J_p = N_{AP} v_{pE} \exp \left( -\frac{q\phi_p}{kT} \right)
\]

(eqn. 2.31)

where,

\( q \phi_n \) and \( q \phi_p \) = potential energy barrier heights for electrons and holes at the B-E junction
\( v_{nB} \) and \( v_{pE} \) = mean speeds (due to the combined effects of drift and diffusion) of electrons at the emitter end of the base and holes at the base end of the emitter respectively.

The above equations are often expressed in terms of diffusion current effects only:

\[
J_n = \frac{qN_{DnB} D_{nB}}{w_b} \exp \left( -\frac{q\phi_n}{kT} \right)
\]

(eqn. 2.32)

\[
J_p = \frac{qN_{AP} D_{pE}}{L_{pE}} \exp \left( -\frac{q\phi_p}{kT} \right)
\]

(eqn. 2.33)

where,

\( D_{nB}, D_{pE} \) = minority carrier diffusion coefficients in the base and emitter respectively
\( L_{pE} \) = hole diffusion length in the emitter region
If the band gap of the emitter is larger than that of the base by $\Delta W_g$, we have:

$$q(\phi_p - \phi_n) = \Delta W_g$$  \hspace{1cm} (eqn. 2.34)

Hence,

$$\frac{I_n}{I_p} = \beta_{\text{max}} = \frac{N_{DE}V_{ab}}{N_{AB}V_{pe}} \exp\left(\frac{\Delta W_g}{kT}\right)$$  \hspace{1cm} (eqn. 2.35)

or in terms of diffusion currents only,

$$\beta_{\text{max}} = \frac{N_{DE}D_{ab}L_{pe}}{N_{AB}D_{pe}W_b} \exp\left(\frac{\Delta W_g}{kT}\right)$$  \hspace{1cm} (eqn. 2.36)

Of the three variables in (eqn. 2.35), $\nu_{nb}/\nu_{pe}$ is least subject to manipulation; hence, for a large $\beta_{\text{max}}$, we need either $N_{DE} >> N_{AB}$ or $\Delta W_g$ to be several times larger than $kT$. Since bandgap differences many times greater than $kT$ is readily obtainable, very high values of $I_p/I_n$ can be achieved almost regardless of the doping ratio. Therefore, the hole injection current $I_p$ becomes negligible and $I_n \approx I_{\text{scr}} + I_{\text{bulk}}$. For a useful, transistor we must still have $I_{\text{bulk}} << I_n$.

If we approximate $I_e$ by $I_n$, we obtain:

$$\beta = \frac{I_n}{I_{\text{scr}} + I_{\text{bulk}}}$$  \hspace{1cm} (eqn. 2.37)

In contrast to homojunction transistors, in a properly designed high gain HBT, the interface recombination current component $I_{\text{scr}}$, can be as small as $I_n/10^3$ making $I_{\text{bulk}}$ the dominant part of $I_b$. Hence, $I_{\text{scr}}$ is neglected beside $I_{\text{bulk}}$; the bulk recombination current density may be written as [38]:

$$J_{\text{bulk}} = \gamma n_e(0) \frac{W_b}{\tau_n}$$  \hspace{1cm} (eqn. 2.38)

where,

$n_e(0)$ = the injected electron concentration at the emitter end of the base
$\tau_n$ = average electron life time in the base
$\gamma$ = a factor between 0.5 and 1 indicating how much electron concentration in the base differs from the electron concentration at the emitter end of the base.
Thus combining (eqn. 2.30), (eqn. 2.37) and (eqn. 2.38) and making the necessary substitutions, we may write the gain as follows:

\[
\beta = \frac{1}{\gamma} \frac{v_{mb} \tau_n}{W_b} \quad \text{(eqn. 2.39)}
\]

This depends on the base doping only through the effect of the base doping on the lifetime; for heavy base doping levels, the lifetimes may be short [47]. Evidently no serious problems from reduced minority carrier lifetimes arise unless the latter drop to the vicinity of \(10^{-10}\) s or lower, at least not for plausible base widths not exceeding 1000 Å.

### 2.4.3 Fundamental Advantages of HBTs

Some of the key benefits of HBTs can be summarised as follows [48]:

- Low base resistance, \(R_b\), as dopings of \(10^{19}\) cm\(^{-3}\) can be used without increasing the hole reverse injection into the emitter
- High base doping ensures that when the base-collector reverse bias is increased, there is minimum change in the base width making the device suitable for high power application
- Lower emitter-base capacitance since wide band gap emitters no longer need to be more highly doped than the base; in microwave application, a lower emitter capacitance reduces the noise figure significantly
- In turn these enhance the high speed performance of HBTs as \(f_{\text{max}}\), the maximum oscillation frequency, is proportional to \(\sqrt{1/R_b}\).
- Since speed determining part of the current path is perpendicular to the surface, and to the first order the speed is determined by the layer thickness which can easily be made much smaller than horizontal dimensions, there is an inherent higher speed potential in bipolar structures than in Field Effect Transistors (FETs).
- For digital switching applications, in HBT based circuits, better threshold voltage control is ensured since in these devices this is dependent on the bandgap of the base and the emitter materials rather than doping dependent as in MESFETs.

### 2.4.4 Abrupt Emitter-Base HBT

A conduction band discontinuity, \(\Delta E_c\), exists in the abrupt emitter-base heterojunction as shown in Figure 2.6. Since in a practical HBT, \(N_{AB} \gg N_{DE}\), this discontinuity appears close
to the base leading to a potential barrier $\Delta E_b$. In addition there is also an insignificant conduction band notch on the base side, $\Delta E_n$; thus, $\Delta E_c \approx \Delta E_b$.

![Figure 2.6: Band diagram of an abrupt emitter/base heterojunction](image)

Hence, for an abrupt junction, (eqn. 2.34) is modified to:

$$q(\phi_p - \phi_n) = q(\Delta E_c + \Delta E_v - \Delta E_b) \approx q(\Delta E_v) = \Delta W_v$$  \hspace{1cm} (eqn. 2.40)

Hence (eqn. 2.35) is also modified and the $\beta$ for a HBT with an abrupt emitter-base junction is now given by:

$$\beta_{abrupt} = \frac{N_{DE} V_{nb}}{N_{AB} V_{pe}} \exp \left( \frac{\Delta W_v}{kT} \right)$$  \hspace{1cm} (eqn. 2.41)

or,

$$\beta_{abrupt} = \frac{N_{DE} D_{nb} L_{pE}}{N_{AB} D_{pE} w_b} \exp \left( \frac{\Delta W_v}{kT} \right)$$  \hspace{1cm} (eqn. 2.42)

### 2.4.5 Common III-V HBT Material Systems

Among all the GaAs-based materials used for HBTs, the most investigated combination has been the AlGaAs/GaAs system which exhibits high current gain, high $f_T$ and $f_{max}$. However, the InP-based lattice matched systems, in particular InP/InGa$_{0.53}$As$_{0.47}$ came into contention primarily because of its bandgap of 0.75eV which is sensitive to 1300nm and 1550nm wavelengths - wavelengths which correspond to the low loss windows of optical fibers and
universally used for long haul optical fiber telecommunications. Apart from the high current driving capacity of HBTs, the material compatibility that the InP/In\textsubscript{0.53}Ga\textsubscript{0.47}As system allows, one can monolithically integrate HBTs with other optoelectronic devices. Also its superior transport properties with respect to the AlGaAs/GaAs system makes it one of the strongest competitors.

The material band alignments for various materials for HBTs were shown in Table 2.2. $\Delta E_v$ for the InP/InGaAs heterojunction is much larger than its $\Delta E_c$ allowing a high injection efficiency without compromising the base doping level. Extremely high doping ($N_{AB}>10^{20} \text{ cm}^{-3}$) has been achieved in InGaAs by GSMBE using Be as the p-type base dopant [49]. High frequency performance is also expected for InGaAs/InP HBTs due to the high electron mobility of InGaAs. In addition, the large $\Gamma$-X and the $\Gamma$-L inter-valley separation ($\Delta E_{\Gamma-X} = 1.0 \text{eV}, \Delta E_{\Gamma-L} = 0.55 \text{eV}$ ) in InGaAs allows large collector voltage swing with high peak carrier velocity. Furthermore, the surface recombination velocity associated with InGaAs, which is $10^3$ lower compared to that of GaAs [50], enables the development of transistors with high current gain but insensitive to collector current density and emitter dimension; thus allowing the latter to be scaled to the sub-micrometer regime.

2.5 Optoelectronic Devices

The performance of an optical link is largely determined by the detector which constitutes one of the dictating elements. Early optical detectors were based on Si which is sensitive to 0.8 to 0.9 $\mu$m and compatible with AlGaAs/GaAs lasers and LEDs. As detection at longer wavelengths (1.1 to 1.6$\mu$m) became necessary, devices based on Ge and III-V compounds became available and research is underway to develop III-V detectors for yet longer wavelengths. This section focuses on the factors behind the evolution of modern optoelectronic devices, basic detector and transmitter operation, the key parameters relating a photodetector to a system, photo receiver configurations and a summary of various detector types with their advantages/disadvantages and typical published performance parameters.

2.5.1 The Case for Fiber-Optic Telecommunication

Immense growth in the telecommunication market has forced large consortium of companies to develop advanced networks and systems based on several aspects of this field: digital signal processing, networks, transmission media, systems and finally components - implementation of novel and highly advanced monolithic optoelectronic integration technology [51].
In the early days of distant telecommunication using modulated microwaves in the 1920’s, the links were generally limited to ‘line of sight’ distances (≈30km). Thus orbiting satellites were needed to relay information over long distances. Today most of these are in geo-stationary orbits (35,800 km above the earth) with only three satellites necessary for continuous coverage to any point on the globe [52]. However, signals are weakened by several orders after travelling these large distances thus requiring high gain antennas and powerful transmitters. A more pertinent problem is the delay and echo in long distance phone calls using these satellites.

The accommodation large traffic requires the use of higher frequency bands. Commercial satellites have been allocated 6 GHz and 4 GHz frequencies for up-links and down-links. Other frequencies include the 12/14 GHz and 20/30 GHz bands for down-links/up-links. But, some of the fundamental limitations of satellite communication systems at frequencies greater than 10 GHz result from a strong interaction of radio waves with rain and ice in the lower atmosphere forcing its capacity to be halved during a rainy period. Also a substantial number of terrestrial relays are required between the exchange and the satellite ground station.

Real interest in optical communication was aroused with the invention of the laser in early 1960’s and proposals for using dielectric waveguides or optical fibers to avoid degradation of the light while propagating, were made almost simultaneously in 1966. Although early systems were lossy (1000 dB/km), today attenuation of less than 0.2 dB/km is easily achieved for a carrier wavelength of 1.55μm [53] - a point that lies at the bottom of the lowest fiber transmission loss window as shown in Figure 2.7.

![Figure 2.7: Loss Characteristics of a Silica Optical Fiber showing the three wavelengths of interest. (After Miya et al [53])](image-url)
This formed the single most influential factor in determining the course of further developments. Thus majority of today’s long haul transmission and receiver systems are geared for operation at the 1.55 \( \mu \)m wavelength. Unlike some of its predecessors, fiber optics technology has many unrivaled advantages [54]:

- **Enormous potential bandwidth**: the optical carrier frequency in the range \( 10^{13} \) to \( 10^{14} \) Hz offers the potential capacity (bandwidth \( \approx 40,000 \) GHz) that is many orders of magnitude greater than the copper cable (< 1 GHz) or microwave radio (< 300 GHz) systems.

- **Low transmission loss**: with losses as low as 0.2 dB/km, this feature has become a major advantage of optical fiber as large repeater spacings (70 to 100 km) may be used in long-haul systems reducing both cost and complexity. Given their bandwidth capability this property provides a totally compelling case for the adoption of optical fiber communication in the majority of long-haul telecommunication applications.

- **Small size and weight**: an optical fiber is often no wider than 50 \( \mu \)m; thus even after applying several protective layers, they are far smaller and much lighter than corresponding copper cables. This is a tremendous boon to alleviating duct congestion in cities.

- **Immunity to interference and cross talk**: they form a dielectric and are free from electromagnetic interference making it easy to reduce optical interference and cross talk.

- **Signal security**: as light from a fiber does not radiate significantly, a transmitted optical signal cannot be obtained non-invasively.

- **System reliability and ease of maintenance**: due to the low loss property, system reliability is generally enhanced in comparison to conventional electrical conductor systems.

By the mid 1990’s, up to 60% of the global telecommunication traffic was said to have been carried over optical fibers [55] and expected to rise to 85% by the millennium. Intercity systems based on optical fibers and using digital transmission with pulse rates ranging from a few hundred Mbit/s to about 2Gbit/s have now been widely implemented. Shorter wavelengths, 820 to 890 nm, are used in short distance links where the higher fiber loss is offset by the low-cost LED/lasers and Si photo diodes which are adequately sensitive.

### 2.5.1.1 Submarine Optical Fiber Systems

In 1858 the first transatlantic cable was laid for telegraphy and transmitted less than a few words per minute. In 1956, the first analog transatlantic telephone cable (TAT-1) became operational and carried 36 voice channels [56]. The analog TAT family grew with further
development and the last such cable, TAT-7, carrying 4200 channels per co-axial cable was fully operational by 1983.

However, an increasing demand by the mid 1980’s for reliable intercontinental telecommunication resulted in the introduction of submarine optical fiber based systems [57,58] later that decade. High capacity cables using a carrier wavelength of 1.3 µm were laid under the Atlantic (TAT-8) and the Pacific oceans (TPC-3) respectively. These can transmit data at 280 Mbit/s per fiber pair; they formed part of the first generation digital lightwave systems [59]. The second generation cables (TAT-9 to TAT-11 and TPC-4) using a carrier wavelength of 1.5 µm and with enhanced transmission rate of 560 Mbit/s per fiber pair are now in operation while the third generation cables (TAT-12 and 13 and TPC-6) are just being commissioned. The latter, using dispersion shifted fibers and a carrier wavelength of 1.55 µm, will implement the first fully optical system using erbium doped fiber amplifiers (EDFAs). The second and third generation cables have extended digital connectivity to the South Pacific, South East Asia and other points [60]. Two such global optical fiber systems are the “SEA-ME-WE-2”, a 560 Mbit/s second generation system, and the FLAG, a third generation system with a maximum expected capacity of 5 Gbit/s.

2.5.2 Optical Detection Principles

Photo detection involving electron excitation from the valence band to the conduction band is referred to as intrinsic absorption while those involving impurity centres within the material is known as extrinsic absorption. However, due to its associated efficiency and fast response it is the former process which is of general interest [61].

In reviewing the basic concepts of photo detection in a p-n junction, it will be shown that only the detectable photo generated electron hole pairs are the ones which give rise to a photo current, $I_{ph}$, in the external circuit of a detector. In order for $I_{ph}$ to have maximum effect in a device, it has to cause maximum change in the output. Although a p-n junction can sense a photo current under forward bias it is over shadowed by the bias dependent thermionic emission current component. Therefore, p-n junction photo detectors operate under reverse bias conditions where all other significant current components are very small and bias independent.

The schematic electron energy band diagram and the spatial carrier concentration diagrams for a p-n junction photo detector are shown in Figure 2.8a and b respectively. The diode is under reverse bias and is illuminated by a super bandgap radiative energy.
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(a) Electron energy diagram

(b) Carrier concentration diagram

Figure 2.8: Schematic diagrams of a reverse biased p-n junction showing intrinsic photo generation processes

Here energy levels are expressed in joules using the notation $W$ (rather than in eV, using $E$); other symbols have the following meanings:

- $x_n =$ depleted n-region
- $x_p =$ depleted p-region
- $L_n = \text{electron diffusion length}$
- $L_p = \text{hole diffusion length}$
- $p_{po} = \text{majority carrier conc. in p-region}$
- $n_{no} = \text{majority carrier conc. in n-region}$
- $n_{po} = \text{minority carrier conc. in p-region}$
- $p_{no} = \text{minority carrier conc. in n-region}$
In order for photo generation to occur, the incident radiation must consist of photons with super bandgap energy, $h\nu$. Also, the radiation must enter the semiconductor material to energetically promote a valence band electron into the conduction band thereby creating an electron-hole pair. The significance of penetration by the incident radiation is discussed in detail in Section 6.3 of this thesis. Assuming the above conditions are met, Figure 2.8 shows that the photo generation can take place in the bulk of either the p or the n regions - depicted by transition G1, in the regions between the bulk and the depletion region - depicted by transition G2 or indeed in the depletion region itself - depicted by transition G3. Each of these three transitions will now be discussed.

If the absorption of an incident photon results in transition G1 the photo generated electron hole pairs in the bulk will randomly scatter within the p or the n-type regions until they recombine as dictated by their respective lifetimes $\tau_n$ and $\tau_p$. This is because they do not experience electric field in the neutral bulk region. Therefore, these will not contribute to a current in the external circuit and are of little use - these cannot be detected.

If the photon penetrates deeper into the material and is absorbed giving rise to transition G2, it will create an electron-hole pair within a diffusion length from the high field depletion region. In the p-region the electrons will be the minority carriers while in the n-region, the minority carriers will be the holes. The diffusion length may be described as the average distance that a minority carrier diffuses in a medium prior to recombining with a majority carrier; conversely, it is the distance in which an excess (in this case brought about by photo generation) minority concentration is reduced to $1/e$ of its peak value. The respective diffusion lengths can be calculated using (eqn. 2.43) and (eqn. 2.44) as follows:

\[
L_n = \sqrt{D_n \tau_n} \quad \text{(eqn. 2.43)}
\]

\[
L_p = \sqrt{D_p \tau_p} \quad \text{(eqn. 2.44)}
\]

where,
- $D_n$ = diffusion constant for electrons ($= \mu_n kT/q$)
- $\tau_n$ = electron lifetime
- $D_p$ = diffusion constant for holes ($= \mu_p kT/q$)
- $\tau_p$ = hole lifetime

Therefore, if a G2 transition takes place in the p-region, the minority electrons experiencing the concentration gradient or the diffusion field will “diffuse” into depletion region boundary. Once it reaches the depletion region, it will fall under the influence of the high drift field.
which will sweep it across to the n-region. An electron traversing the junction contributes a charge \( q^- \) to the current flow in the external circuit. Similarly, a \( G_2 \) transition in the n-region will cause a photo generated hole to traverse the junction and give rise to another component of the photo current.

Finally a \( G_3 \) transition will cause both the photo generated electron and hole to give rise to a drift current; the electron will traverse to the reverse biased n-region while the hole to travel in the opposite direction. Since each carrier traverses a distance which is less than the full junction width, the contribution of this process to charge flow in the external circuit is \( q^- \).

In practice, the last process is the most desirable since each absorption gives rise to a charge \( q^- \) and delayed current response caused by finite diffusion time is avoided.

2.5.2.1 The Key Parameters Relating a Photodetector to an Optical System

Some of the key parameters which relate a photo detector to the ultimate system where it is applied include its sensitivity, dynamic range, quantum efficiency, responsivity, internal gain, bandwidth and noise. The basic goal is to achieve the lowest possible noise at a given bandwidth or data rate.

The sensitivity of a photo detector is defined as the minimum mean optical power needed to achieve a given bit error rate, BER (CCITT standard requires a BER of \( 10^{-10} \)). The exact expressions for sensitivity vary according to the particular type of detector. Its dynamic range is the range of input power levels over which the BER is acceptable [62]. The quantum efficiency, \( \eta \), and the responsivity, \( R \), are interlinked; the \( \eta \) is essentially the efficiency of converting an incident photon (optical power) into useful photo current, \( I_{ph} \), whereas the \( R \) is the amount of \( I_{ph} \) obtained for a unit of incident optical power, \( P_0 \). These last two parameters are wavelength dependent as discussed later in section 4.5. The internal gain of a detector refers to the generation of secondary electron-hole pairs created by the primary photo generated pair as in Avalanche Photo Diodes (APDs) or the electrical gain, \( \beta \), of bipolar transistor based photo detectors. The bandwidth, \( B \), refers to the range of frequencies over which the detector provides useful output at a pre-defined level (e.g. 3dB). Finally, the noise is a term which refers to spurious output in the absence of light; thus thermally generated dark current and surface and other leakage currents all add to this unwanted “signal” and contribute to the noise which essentially limits the sensitivity of the detector [61]. Terms often used to quantify this complex parameter include “signal to noise ratio” (SNR) and “noise equivalent power” (NEP) which is the incident optical power, at a given wavelength, necessary to obtain a \( I_{ph} \) equivalent to the rms noise current within a unit bandwidth \( B \).
There is often a fundamental trade-off between the sensitivity and the bandwidth of a detector. For example, in the case of a p-i-n detector with a FET pre-amplifier, a large resistor may be needed to extract a useful voltage to drive the gate of the FET. In doing so, however, the RC constant becomes large which limits the bandwidth of the receiver.

2.5.3 p-n, p-i-n and Avalanche Photo Diodes (APDs)

Photo diodes can be broadly categorised into two types: those without internal gain such as p-n and p-i-n diodes and those with such as APDs. The penetration depth of light before it is absorbed within a material increases with its wavelength (see section 6.3). Thus a wider depletion region is necessary for long wavelength operation. In the p-n junction, this is achieved by making the n-type material so lightly doped that it can be considered intrinsic; an n+ layer is added to reduce ohmic contact. This modified device is known as a p-i-n photo diode [61]. The intrinsic layer is wide enough to maximise absorption for a given wavelength and the low doping means it is fully depleted under normal reverse bias resulting in fast collection of photo generated electron hole pairs. Due to the spectral limitations of Si and thermal instabilities and large dark currents associated with Ge, p-i-n diodes have been designed and fabricated using InGaAs which are sensitive over 0.95 to 1.65 \( \mu \text{m} \) wavelength range [63] and have dark currents in the pA range at room temperature [64]. Substrate entry heterojunction p-i-n based on InGaAs p+ and i layers and InP n layers have been used to eliminate absorption in the top p+ layer. However, this design suffers from charge trapping in the InGaAs/n-InP heterointerface although it is not a severe limitation to its performance [65].

In Avalanche Photo Diodes (APD), the structure of the basic p-n diode is further modified to create an extremely high electric field; the APD consists of a n-p-i-p+ type layer structure. In addition to the depletion n-p region where majority of absorption takes place, the high field region (i region) accelerates the primary photo generated pairs to acquire sufficient energy to excite new electron-hole pairs by impact ionization [61]. This is known as carrier multiplication; hence these devices have inherent gain. In order to minimise noise, the electric field at avalanche breakdown must be as low as possible. In Si, this has been achieved by using a reach through structure (RAPD) where the multiplication region is much wider than the n-p region. Much of the material problems associated with Si and Ge p-i-n diodes are also relevant to APDs and heterojunction devices have been realised using various compound semiconductor material systems including InGaAs/InP. However, the narrow bandgap of InGaAs gives rise to unacceptably high level of band-to-band defect tunneling currents which precede avalanche field. In common with the Si RAPD, this problem is significantly reduced by using a separate absorption and multiplication region in the SAM-
APDs with the gain occurring at InP p-n junction where tunneling is much less [66]. As in InGaAs/InP p-i-n, the issue of charge trapping at the heterointerface discontinuity is also a limitation in these APDs. However, Campbell et al [67] have reported the use of a InGaAsP (with a bandgap located between InGaAs and InP) quaternary grading layer to smooth out the discontinuity and hence improve speed performance in separate absorption, grading and multiplication (SAGM) APDs. Noise arising from multiplication region in APDs has been addressed by Capasso et al [68] by incorporating a super lattice structure (SL) in AlGaAs/GaAs and Kagawa et al [69] in the InGaAs/InAlAs SL-SAM-APDs.

2.5.4 ITO/n-GaAs Schottky Photo Diodes

The use of a Schottky barrier photo diode has many advantages for very high speed applications. In common with a conventional p-i-n detector, the absorption layer thickness can be engineered to obtain the optimum compromise between external quantum efficiency and detector bandwidth. An advantage however, is that there is no slow component associated with minority carrier effects in the p+ region of a p-i-n photo diode [70]. Planar Pt/n-GaAs Schottky diodes with 100 GHz bandwidth have been reported by Wang et al [71]; the metal thickness was only 100Å to allow for optocoupling.

An inherent disadvantage of the Schottky photo diode, however, is the high series resistance and low efficiencies arising from the semi-transparent metal layer. This is apparent in the relatively low quantum efficiency of 19% and high series resistance of 190Ω obtained by Emeis et al in their p-InGaAs Schottky diodes (for operation at 1.3µm wavelength) with 50Å Ni semi-transparent metal contact [72].

Using a practically transparent and highly conductive layer of Indium Tin Oxide (ITO) to form the metal/semiconductor junction solves both these problems [73]. Figure 2.9 shows the band diagram of such a device.
The absorption layer is usually lightly doped to maximise depletion and is situated directly underneath the metal contact. Light enters through the transparent ITO contact and creates photo generated electron-hole pairs. These are then swiftly separated by the built-in depletion field giving rise to a photo current. The speed of response of such a device depends on the transit time of photo-generated carriers across the depletion region, the junction capacitance and parasitic circuit element contribution. In a monolithic structure, device isolation, achieved by either proton bombardment or mesa etch or a combination of both, reduces these parasitics. Furthermore, a planar structure is suitable for monolithic integration with other circuit elements such as HBTs or HEMTs.

Further discussion on Schottky diodes and photo detectors are presented in section 6.1

2.5.5 Transparent-Gate High Electron Mobility Transistors (TG-HEMTs)

The use of GaAs Metal Semiconductor Field Effect Transistors (MESFETs) and AlGaAs/GaAs High Electron Mobility Transistors (HEMTs) as optoelectronic detectors have been recently reported [74,75]. These are both essentially field effect devices where current is transported laterally through a channel between two horizontal electrodes, source and drain, that can be modulated by a Schottky electrode placed at an intermediate lateral location [76]. The more advanced heterojunction HEMT device usually consists of epitaxially grown n-type AlGaAs layer on an undoped GaAs layer grown on a semi insulating GaAs layer. The channel is formed by mobile charge accumulation at the heterointerface since electrons from the wider bandgap AlGaAs “supply layer” transfer across into the undoped GaAs in order to
occupy a lower energy state. Extremely high electron mobility results from diminished scattering due to ionised impurity as the coulombic field within the undoped GaAs crystal lattice is greatly reduced [77].

As in the ITO/n-GaAs Schottky photo diodes, radiation with energy greater than the bandgap of AlGaAs gives rise to a photo-generated electron-hole pair in the supply layer directly above the channel. This pair is separated by the built-in Schottky field giving rise to a photo current and corresponding photo voltage across the junction. In turn, this photo voltage effectively reduces the channel width and can be used for the desired optical control [78]. We have recently shown that using a transparent ITO gate enhances this control [79]. On the other hand, a photo conductive effect dominates if the energy of the incident radiation is between the bandgaps of the AlGaAs and GaAs; in this case, electron-hole pairs are generated in the GaAs channel and are separated by the lateral source-drain electric field thus adding to the drain current.

In comparison with the Schottky photo diode, the responsivity of these devices is many times greater as a direct consequence of the in-built gain of the FET structure. An inherent limitation of these devices as optical detectors however arises from the fact that the combined vertical depth of the AlGaAs and GaAs channel layers, typically 0.1µm, are inadequate to ensure maximised photo absorption.

2.5.6 Heterojunction Photo Transistors (HPTs)

With the problems encountered with APDs in the 1970’s for long wavelength use and the advent of high speed HBTs in addition to other fundamental benefits offered by these devices, renewed interest in (heterojunction) photo transistors (HPTs) as optical detectors has been aroused. The HPT offers the dual function of detection and amplification in a single device. In comparison with its rivals such as p-i-n/FET or APD/FET photo receiver combinations, this device is a particularly attractive alternative because of its relatively simple structure, ease of fabrication and integrated nature [80]. From an optical communication point of view, HPTs can be easily integrated monolithically in existing MMIC and OEIC processes resulting in high reliability and low parasitic noise [81].

Studies using HBTs with opaque emitter contacts show excellent suitability of these devices as photo detectors [82] and mixers in coherent photo receivers [83] in terms of optical performance where signal to noise ratios in excess of 30dB have been obtained. Optoelectronic mixing in HPTs has considerable potential for simplification of the
optical/electrical interfaces in some configurations of these systems. Mixing in the HPT is easily realised since the base terminal can be pumped either optically or electrically.

In the photo transistor, radiation incident on the device passes through the wide gap emitter unattenuated and is absorbed in the base, base-collector depletion region and bulk collector. Under normal common emitter operation mode, the base-collector junction is reverse biased. Hence it can be likened to a p-i-n photo diode (the collector doping is relatively very low). The base-collector junction acts as the light gathering element or the absorption layer. Internal gain is achieved through normal transistor action whereby light absorbed affects the base current (effectively adding to the $I_{ cbo}$ component) giving multiplication of photo current through the device. The optical gain, $G$, for a heterojunction photo transistor is given by [84,85]:

$$G \approx \beta \eta$$  \hspace{1cm} (eqn. 2.45)

where,

$\beta$ = electrical gain of transistor
$\eta$ = quantum efficiency of the base-collector photo diode

In terms of responsivity, this can be re-written as :

$$R_{HPT} \approx \beta R_{Diode}$$  \hspace{1cm} (eqn. 2.46)

where,

$R_{HPT}$ = responsivity of the heterojunction photo transistor
$R_{Diode}$ = responsivity of the base-collector photo diode

The quantum efficiency in (eqn. 2.45) is a function of the device parameters only and is independent of the current gain. Other aspects of the HPT are discussed later in Section 6.2.

2.5.7 Light Emitting Diodes (LED) and Vertical Cavity Surface Emitting Lasers (VCSEL)

A detailed theoretical discussion on the operation of LEDs and LASERs is clearly beyond the scope of this thesis. Yet, like detectors these transmitting devices constitute an inseparable part of the optical link. Solid state implementation of these devices essentially involve a p-n junction designed specifically for light emission rather than absorption. In the case of the LED, the p-n junction is formed using degenerate semiconductors to ensure forward current is dominated by the recombination process resulting in spontaneous emission of photons [86].
LEDs have been realised using a host of III-V compounds ranging from GaN for ultraviolet, GaAs for blue through to near infra-red and InGaAsP for emission beyond this spectral range. Unlike LEDs, laser operation is dominated by stimulated emission of light which results in highly monochromatic radiation. Laser modulation is easily achieved by modulating the forward current. Since the photon lifetimes are very short, high speed modulation can be realised. AlGaAs/GaAs lasers are used for 0.8 - 0.9 \( \mu \text{m} \) emissions while longer wavelengths of 1.3 - 1.55 \( \mu \text{m} \) are catered for by the InGaAsP/InP system.

Internal reflection and substrate absorption losses limit the external quantum efficiencies of LEDs. A significant portion of the drive current crosses the p-n junction directly beneath the contact, generating light that is obscured. Given that at the p-n junction the emitted light intensity is at its peak, this is particularly undesirable. The high resistances associated with a semi-transparent metal electrode lead to rapid decrease in junction current density due to its exponential dependence on the voltage; in turn this significantly reduces the emission from points at a lateral distance from the contact. Therefore, the use of a transparent contact not only allows the entire junction area to emit (which would otherwise be obscured) but it does so with uniformity. Aliyu et al have reported very low threshold voltage of 1.7V for 20 mA in their study using ITO contacts on AlGaInP visible LEDs [87].

Vertical Cavity Surface Emitting Lasers have recently aroused interest in a number of fields including fiber optic communication and optical computing. As the name suggests, VCSELs use an orthogonal cavity for light amplification rather than the common lateral Fabry-Perot approach that is associated with an edge emitting laser. High reflection is made possible by epitaxial growth of Bragg reflectors. As in LEDs, the optical path is obscured by the route of the injection current. We have demonstrated that ITO can be used to realise InGaAs/GaAs VCSELs for the first time resulting in very low threshold currents of 20 mA at room temperature [88].

2.5.8 Principal Receiver Configurations

Optical receivers can be classed into three basic categories: direct detection; coherent or heterodyne detection; and optically pre-amplified and tunable direct detection.

In direct detection communication systems, where the photo detector responds merely to the intensity of the incident optical signal, good sensitivity or large signal to noise ratios are very important. Since the noise is dominated by thermal sources in the preamplifier, the sensitivity can be improved either by applying gain or reducing the noise [62]. To this end, the most
Chapter 2: Background Theory and Literature Survey

A popular approach has been in favour of the p-i-n/FET combination [89] rather than single APDs. Other common direct detection based implementations involve using p-i-n/HBT [90] and Schottky/HEMT [91] photo receivers.

Coherent detection, or mixing, involves amplifying the incoming signal by multiplying it with a local oscillator. This has two advantages over direct detection: (a) the receiver sensitivity can approach the Shot noise limit of the signal and (b) much greater wavelength selectivity allows many more channels to be carried at different wavelengths by the same fiber. Heterodyne receivers have also been implemented in a wide range of device combinations: p-i-n/FET [92], p-i-n/HEMT [93]. However, in their comparison of a wide range of heterodyne receivers, Urey et al [83] reported that in terms of the available intermediate frequency (IF) signal/noise ratio, the best performance was obtained using HPTs as mixers.

Optical pre-amplification refers to a relatively new technology which has wide ranging implications. Majority of today’s developmental work is devoted to the erbium doped fiber amplifier (EDFA) [55]. These utilise a silica fiber with a doped core to provide a medium which affords gain when optically pumped at an appropriate wavelength - presently 980 nm or 1480 nm because of the availability of solid state lasers which couple sufficient power at these wavelengths. The signal is optically amplified en route to the detector end of the link; this reduces component count, increases reliability and opens up full bandwidth of the fiber windows between switching centres. The sensitivity of pre-amplified receivers exceeds that of coherent systems at high bit rates representing a major cost advantage in its favour since it essentially uses a direct detection design; tuning is achieved by selecting a suitable filter.

2.5.9 A Brief Comparison Between Various Types of Detectors

A summary comparison with some of the key performance parameters for various types of optical detector devices is shown in Table 2.3. These represent typical figures quoted in the literature for advanced III-V detectors and not necessarily the best data which is now available. Following the discussion on individual devices in previous sections, the purpose of this table is to present a “at a glance” figures of merit for these devices. For a more careful comparison, one needs to take into account several other factors such as material systems, the layer structures and the wavelength of the optical radiation amongst others; one such performance comparison between HPTs, p-i-n/FETs and APD/FETs has been made by Tabatabaie-Alavi et al [80]. In some cases, where no data is reported, an estimate is presented (e.g. bandwidth estimated from quoted impulse response for the device) or left empty where this is not possible.
It can be noticed from the above comparison that p-i-n devices are designed to provide high speed whereas APDs are essentially high gain devices. Since from a system point of view, the product of the gain and the bandwidth is important, there will a region of overlap where either device may be equally suitable. Another noticeable feature of this table is the inherent trade-off between the quantum efficiency, $\eta$, and the bandwidth of the detector; the two ITO/n-GaAs Schottky detectors [70,73] can be used to illustrate this point at a first order comparison: a slightly (10%) narrower absorption region enhances speed at the cost of lowering the $\eta$. HPTs have also come into contention with advancements in device technology and material growth techniques; these devices combine high speed and high gain and can be used as mixers. Finally, it is clearly seen that the use of ITO as both transparent Schottky and emitter ohmic contacts improves the $\eta$ without fundamentally reducing the bandwidth.
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Appendix A: List of Publications

A.1 Journal / Letter Publications


A.2 Publications in Conference, Colloquium and Workshop Proceedings


Appendix B: Processing Steps for Liftoff and Etch Lithography

Ideal sample size for processing: between 1cm x 1cm and 2.5cm x 2.5cm.

B.1 Steps for Liftoff lithography

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>Conditions/Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>De-greasing</td>
<td>Clean in TCE, acetone, methanol - at 60°C for 10 mins. in each (skip TCE if this is not the first photolithography stage)</td>
</tr>
<tr>
<td>2</td>
<td>Rinse</td>
<td>Rinse in running D.I. water for 5 minutes</td>
</tr>
<tr>
<td>3</td>
<td>Pre-bake</td>
<td>Blow dry sample then bake at 160°C for 30 mins.</td>
</tr>
<tr>
<td>4</td>
<td>Photoresist (P.R.)</td>
<td>Apply P.R. (Shipley 1400-27) to entire surface using a clean pipette; spin at 4,500 rpm for 35 secs. to obtain a film thickness of app. 1µm.</td>
</tr>
<tr>
<td>5</td>
<td>Soft bake</td>
<td>Bake sample at 70°C for 30 minutes, then allow sample to cool prior to alignment</td>
</tr>
<tr>
<td>6</td>
<td>Prepare Mask</td>
<td>Clean mask in acetone and blow dry carefully in N₂, then place mask facing down in the aligner</td>
</tr>
<tr>
<td>7</td>
<td>Alignment</td>
<td>Carefully remove any P.R. residue from the back of sample using acetone prior to placing sample on the aligner tray; insert and then raise the tray to bring the sample into “contact”; lower slightly to the “separation” position to facilitate alignment; once satisfactory alignment to the mask has been achieved, carefully raise the tray to the “contact” position once again.</td>
</tr>
<tr>
<td>8</td>
<td>UV Exposure</td>
<td>Expose using UV light for 15 secs.</td>
</tr>
<tr>
<td>9</td>
<td>Chlorobenzene</td>
<td>Soak in chlorobenzene (inside the fume cupboard) for 4 mins. then carefully blow dry using N₂</td>
</tr>
<tr>
<td>10</td>
<td>Post bake</td>
<td>Bake sample at 70°C for a further 15 mins.</td>
</tr>
<tr>
<td>11</td>
<td>Develop</td>
<td>Soak in a 1 Microposit developer : 1 H₂O solution for roughly 1 min; check under microscope to ensure “windows” have opened adequately; do a final soak in a fresh developer solution for a further 15 secs to remove trace P.R.</td>
</tr>
<tr>
<td>12</td>
<td>De-oxidise</td>
<td>Finally, etch in 10% HCl solution for 15 secs. prior to metalisation.</td>
</tr>
</tbody>
</table>

Table B1: Processing steps for lift-off lithography
B.2 Steps for Etch lithography

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>Conditions/Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 4</td>
<td></td>
<td>Same as lift-off lithography, see Table B1</td>
</tr>
<tr>
<td>5</td>
<td>Soft Bake</td>
<td>Bake sample at 95°C for 30 minutes, then allow sample to cool prior to alignment</td>
</tr>
<tr>
<td>6 - 8</td>
<td></td>
<td>Same as lift-off lithography, see Table B1</td>
</tr>
<tr>
<td>9</td>
<td>Develop</td>
<td>Soak in a 1 Microposit developer : 3 H2O solution for roughly 90 secs.; check under microscope to ensure “windows” have opened adequately; do a final soak in a fresh developer solution for a further 15 secs to remove trace P.R.</td>
</tr>
<tr>
<td>10</td>
<td>Hard Bake</td>
<td>Bake sample at 115°C for 30 minutes, then allow sample to cool prior to etching in required solution</td>
</tr>
</tbody>
</table>

Table B2: Processing steps for etch lithography
C.1 Settings for Schottky diode parameter extractions

Device configuration: positive terminal to SMU1; negative terminal to SMU3.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Source Set-up</th>
<th>Channel Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMU1</td>
<td>VF</td>
<td>Name Var1 Var2</td>
</tr>
<tr>
<td>SMU2</td>
<td>-</td>
<td>Name</td>
</tr>
<tr>
<td>SMU3</td>
<td>COM</td>
<td>Mode Functio V I VAR1</td>
</tr>
<tr>
<td>SMU4</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Table C1.1: Typical SPA settings for measuring the output characteristics of a Schottky diode

C.2 Settings for HBT parameter extractions

Device configuration: emitter to SMU1; base to SMU2; collector to SMU3.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Source Set-up</th>
<th>Channel Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMU1</td>
<td>VCE</td>
<td>Name Var1 Var2</td>
</tr>
<tr>
<td>SMU2</td>
<td>IB</td>
<td>Name</td>
</tr>
<tr>
<td>SMU3</td>
<td>IC</td>
<td>Mode Functio V I VAR1</td>
</tr>
<tr>
<td>SMU4</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Table C2.1: Typical SPA settings for measuring the output characteristics of a HBT
Table C2.1: Typical SPA settings for measuring the output characteristics of a HBT Gummel plot

<table>
<thead>
<tr>
<th>Channel</th>
<th>Name</th>
<th>Source</th>
<th>Mode</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMU1</td>
<td>VE</td>
<td>IE</td>
<td>COM</td>
<td>CONST</td>
</tr>
<tr>
<td>SMU2</td>
<td>VB</td>
<td>IB</td>
<td>V</td>
<td>VAR1</td>
</tr>
<tr>
<td>SMU3</td>
<td>VCE</td>
<td>IC</td>
<td>V</td>
<td>VAR1'</td>
</tr>
<tr>
<td>SMU4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source Set-up</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Var1</td>
<td>Var2</td>
</tr>
<tr>
<td>Sweep Mode</td>
<td>linear</td>
<td>-</td>
</tr>
<tr>
<td>Start</td>
<td>0.0V</td>
<td>-</td>
</tr>
<tr>
<td>Stop</td>
<td>1.6V</td>
<td>-</td>
</tr>
<tr>
<td>Step</td>
<td>0.01V</td>
<td>-</td>
</tr>
<tr>
<td>No. of steps</td>
<td>160</td>
<td>-</td>
</tr>
<tr>
<td>Compliance</td>
<td>100mA</td>
<td>-</td>
</tr>
<tr>
<td>VAR1’ ratio = 1, VAR1’ offset = 0.0V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant Source Compliance</td>
<td>VE COM</td>
<td>0.0V</td>
</tr>
</tbody>
</table>

Table C2.2: Typical SPA settings for measuring the Gummel plot of a HBT

DC Gain, $\beta$

<table>
<thead>
<tr>
<th>Channel</th>
<th>Name</th>
<th>Source</th>
<th>Mode</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMU1</td>
<td>VE</td>
<td>IE</td>
<td>COM</td>
<td>CONST</td>
</tr>
<tr>
<td>SMU2</td>
<td>VB</td>
<td>IB</td>
<td>V</td>
<td>VAR1</td>
</tr>
<tr>
<td>SMU3</td>
<td>VCE</td>
<td>IC</td>
<td>V</td>
<td>CONST</td>
</tr>
<tr>
<td>SMU4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

USER FUNCTION:
1. $HFE = \frac{IC}{IB}$
2. $AC = \frac{\Delta IC}{\Delta IB}$

<table>
<thead>
<tr>
<th>Source Set-up</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Var1</td>
<td>Var2</td>
</tr>
<tr>
<td>Sweep Mode</td>
<td>linear</td>
<td>-</td>
</tr>
<tr>
<td>Start</td>
<td>0.1V</td>
<td>-</td>
</tr>
<tr>
<td>Stop</td>
<td>3.9V</td>
<td>-</td>
</tr>
<tr>
<td>Step</td>
<td>0.05V</td>
<td>-</td>
</tr>
<tr>
<td>No. of steps</td>
<td>77</td>
<td>-</td>
</tr>
<tr>
<td>Compliance</td>
<td>100mA</td>
<td>-</td>
</tr>
<tr>
<td>Constant Source Compliance</td>
<td>VE COM</td>
<td>0.0V</td>
</tr>
</tbody>
</table>

Table C2.3: Typical SPA settings for measuring the DC gain of a HBT
Emitter contact resistance, $R_{ee'}$:

<table>
<thead>
<tr>
<th>Channel</th>
<th>Name</th>
<th>Source</th>
<th>Var1</th>
<th>Var2</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMU1</td>
<td>VE</td>
<td>IE</td>
<td>COM</td>
<td>CONST</td>
</tr>
<tr>
<td>SMU2</td>
<td>VB</td>
<td>IB</td>
<td>I</td>
<td>VAR1</td>
</tr>
<tr>
<td>SMU3</td>
<td>VCE</td>
<td>IC</td>
<td>I</td>
<td>CONST</td>
</tr>
<tr>
<td>SMU4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Name</th>
<th>Var1</th>
<th>Var2</th>
</tr>
</thead>
<tbody>
<tr>
<td>IB</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Sweep Mode: linear
Start: 0.0A
Stop: 5.0mA
Step: 10μA
No. of steps: 501
Compliance: 2.0V

<table>
<thead>
<tr>
<th>Constant</th>
<th>Source</th>
<th>Compliance</th>
</tr>
</thead>
<tbody>
<tr>
<td>VE</td>
<td>COM</td>
<td>0.0V 105.0mA</td>
</tr>
<tr>
<td>IC</td>
<td>I</td>
<td>0.0A 2.0V</td>
</tr>
</tbody>
</table>

Table C2.4: Typical SPA settings for measuring the emitter contact resistance, $R_{ee'}$, a HBT

Collector contact resistance, $R_{cc'}$:

<table>
<thead>
<tr>
<th>Channel</th>
<th>Name</th>
<th>Source</th>
<th>Var1</th>
<th>Var2</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMU1</td>
<td>VE</td>
<td>IE</td>
<td>I</td>
<td>CONST</td>
</tr>
<tr>
<td>SMU2</td>
<td>VB</td>
<td>IB</td>
<td>I</td>
<td>VAR1</td>
</tr>
<tr>
<td>SMU3</td>
<td>VCE</td>
<td>IC</td>
<td>COM</td>
<td>CONST</td>
</tr>
<tr>
<td>SMU4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Name</th>
<th>Var1</th>
<th>Var2</th>
</tr>
</thead>
<tbody>
<tr>
<td>IB</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Sweep Mode: linear
Start: 0.0A
Stop: 5.0mA
Step: 10μA
No. of steps: 501
Compliance: 2.0V

<table>
<thead>
<tr>
<th>Constant</th>
<th>Source</th>
<th>Compliance</th>
</tr>
</thead>
<tbody>
<tr>
<td>IE I</td>
<td>0.0A</td>
<td>2.0V</td>
</tr>
<tr>
<td>VCE COM</td>
<td>0.0V</td>
<td>105.0mA</td>
</tr>
</tbody>
</table>

Table C2.5: Typical SPA settings for measuring the collector contact resistance, $R_{cc'}$, of a HBT
Appendix D: Mathematical Derivations

D.1 Two derivations for the doping concentration, $N_D$.

The capacitance, $C$, of Schottky diode as a function of the applied bias, $V_{app}$, (see section 4.3) is given by:

$$C = \frac{\varepsilon_o \varepsilon_r A}{\sqrt{qN_D (V_{bi} - V_{app})}}$$

(eq. D1.1)

Therefore,

$$\frac{1}{C^2} = \frac{2}{qN_D \varepsilon_o \varepsilon_r A^2} (V_{bi} - V_{app})$$

(eq. D1.2)

D1.1 The first derivation

Differentiating (eqn. D1.2) w.r.t. $V_{app}$ yields:

$$\frac{d(1/C^2)}{dV_{app}} = -\frac{2}{qN_D \varepsilon_o \varepsilon_r A^2}$$

(eq. D1.3)

Rearranging in terms of $N_D$:

$$N_D = -\frac{2}{q \varepsilon_o \varepsilon_r A^2} \cdot \frac{dV_{app}}{d(1/C^2)}$$

(eq. D1.4)

D1.2 The second derivation

Simplifying (eqn. D1.1) gives:

$$C = \sqrt{\frac{qN_D \varepsilon_o \varepsilon_r A^2}{2}} \cdot \frac{1}{\sqrt{(V_{bi} - V_{app})}}$$

(eq. D1.5)

Differentiating (eqn. D1.5) w.r.t. $V_{app}$ yields:
Appendix D: Mathematical Derivations

\[
\frac{dC}{dV_{app}} = \sqrt{\frac{qN_D \varepsilon_o \varepsilon_r A^2}{2}} \cdot \left(\frac{1}{2} \left(V_{bi} - V_{app}\right)^{-3/2}\right) \quad \text{(eqn. D1.6)}
\]

But from (eqn. D1.5),

\[
\frac{1}{\sqrt{V_{bi} - V_{app}}} \text{ or } \left(V_{bi} - V_{app}\right)^{-1/2} = \frac{C}{\sqrt{\frac{qN_D \varepsilon_o \varepsilon_r A^2}{2}}} \quad \text{(eqn. D1.7)}
\]

Hence, substituting (eqn. D1.7) in (eqn. D1.6), we obtain:

\[
\frac{dC}{dV_{app}} = \sqrt{\frac{qN_D \varepsilon_o \varepsilon_r A^2}{2}} \cdot \left(\frac{1}{2} \left(\frac{C}{\sqrt{\frac{qN_D \varepsilon_o \varepsilon_r A^2}{2}}}\right)^3\right)
\]

\[
= \frac{1}{2} \left(\frac{C^3}{\sqrt{\frac{qN_D \varepsilon_o \varepsilon_r A^2}{2}}}\right)^2 \quad \text{(eqn. D1.8)}
\]

\[
= \frac{C^3}{qN_D \varepsilon_o \varepsilon_r A^2}
\]

Rearranging in terms of \(N_D\):

\[
N_D = \frac{C^3}{q \varepsilon_o \varepsilon_r A^2 \left(\frac{dC}{dV_{app}}\right)^{-1}} \quad \text{(eqn. D1.4)}
\]

D.2 Derivation of built-in potential at the base-emitter heterojunction, \(V_{bi(B-E)}\), of a HBT

The analytical expression for \(V_{bi(B-E)}\) is given by:

\[
V_{bi(B-E)} = E_{gB} + \Delta E_C + \frac{kT}{q} \ln \left(\frac{N_{DE}N_{AB}}{N_{cE}N_{vB}}\right) \quad \text{(eqn. D2.1)}
\]
which can be re-written as:

$$V_{bi}(B-E) = E_{gB} + \Delta E_C + \frac{kT}{q} \ln \left( \frac{N_{DE}N_{AB}}{n_{ib}n_{iE}} \right) + \frac{kT}{q} \ln \left( \frac{n_{ib}n_{iE}}{N_{CE}N_{VB}} \right)$$  \hspace{1cm} (eqn. D2.2)

But recall that,

$$n_{ib} = \sqrt{N_{cb}N_{vb}} \cdot \exp \left( -\frac{qE_{gB}}{2kT} \right)$$  \hspace{1cm} (eqn. D2.3)

and,

$$n_{iE} = \sqrt{N_{ce}N_{ve}} \cdot \exp \left( -\frac{qE_{ge}}{2kT} \right)$$  \hspace{1cm} (eqn. D2.4)

Thus, the final term in (eqn. D2.2) can be expressed as:

$$\frac{kT}{q} \ln \left( \frac{n_{ib}n_{iE}}{N_{ce}N_{vb}} \right) = \frac{kT}{q} \ln \left( \frac{\sqrt{N_{cb}N_{ve}}}{\sqrt{N_{ce}N_{vb}}} \right) \cdot \frac{1}{2} \left( E_{gB} + E_{ge} \right)$$  \hspace{1cm} (eqn. D2.5)

And therefore, (eqn. D2.2) can now be written as:

$$V_{bi}(B-E) = E_{gB} + \Delta E_C + \frac{kT}{2q} \ln \left( \frac{N_{cb}N_{ve}}{N_{ce}N_{vb}} \right) + \frac{kT}{q} \ln \left( \frac{N_{DE}N_{AB}}{n_{ib}n_{iE}} \right) - \frac{1}{2} \left( E_{gB} + E_{ge} \right)$$  \hspace{1cm} (eqn. D2.6)

But since, \( E_{ge} > E_{gB} \), and

$$\Delta E_g = E_{ge} - E_{gB}$$  \hspace{1cm} (eqn. D2.7)

Hence we obtain the desired expression for the \( V_{bi} \) of a heterojunction:

$$V_{bi}(B-E) = \Delta E_C - \frac{\Delta E_g}{2} + \frac{kT}{2q} \ln \left( \frac{N_{cb}N_{ve}}{N_{ce}N_{vb}} \right) + \frac{kT}{q} \ln \left( \frac{N_{DE}N_{AB}}{n_{ib}n_{iE}} \right)$$  \hspace{1cm} (eqn. D2.8)