CHAPTER 1

Introduction and Scope of the Thesis.

1.1 Introduction

Semiconductor heterostructures supporting low dimensional electrons and holes as carriers, have generated much interest in recent years [1-4]. The carriers have interesting properties that lead to the design of sophisticated communication circuits, super fast computers and opto-electronic circuitry [5-8]. The low dimensional systems are important for their possible technological applications. They are also interesting from the point of view of verifying many fundamental theories of physics.

A semiconductor heterostructure is formed by interfacing two monocrystalline, lattice matched semiconducting materials having different bandgap energies [9]. When the two semiconductors have the same type of conductivity, the junction is called an isotype heterojunction (Fig 1.1). When the conductivity types differ, the junction is called an anisotype heterojunction (Fig 1.2). An approximately triangular narrow potential well is formed at the heterojunction. A quantum well is formed by sandwiching a very thin layer of a lower bandgap semiconductor between two larger bandgap semiconductors so that a square potential well is formed (Fig.1.3). There are other variations of the heterostructure as well.

When the characteristic dimensions i.e., the width of the potential well thus formed, becomes comparable to the de-Broglie wavelength of the carriers i.e., the holes and the electrons, the carrier gases get trapped in the well and enter a quantum regime. Their energies and motion become quantised in one or two dimensions along the very narrow and finite well widths. These carriers are then called low dimensional because their motion in the direction of potential variation within the well gets restricted [10-12]. The freedom of free movement of the carriers is no longer present in all the three dimensions as it is expected for the bulk semiconductor. This was first predicted by Shreiffer [10]. If the quantisation is in
Fig 11 (a) n-n (b) p-p isotype heterojunctions
Fig 1.2 (a) n-p semiconductors before contact, (b) n-p heterojunction, (c) p-n heterojunction
Fig 1 3. Formation of a Square Well
one direction and freedom of movement is present in the other two dimensions, the system is a two dimensional gas. The carriers then move freely along a plane parallel to the interface. The wave function describing an ideal two-dimensional carrier gas is a delta function and the carriers are strictly confined to a plane with no extension outside. It is a sheet like distribution. However, in reality, although there is no propagation along the transverse direction, yet the carriers are not strictly confined over a plane of zero thickness but smeared along a finite width in the direction of quantisation of motion. Due to this spread of the carrier distribution, the carriers are called quasi two-dimensional. If the quantisation is along two directions, then the system is one-dimensional. The carriers in such a system move along a line i.e. the axis of a wire. When the carriers are electrons, the systems are two-dimensional or one-dimensional electron gas systems (2DEG or 1DEG) and when the carriers are holes, the systems are called two-dimensional or one-dimensional hole gas systems (2DHG or 1DHG).

The properties of the low dimensional gases make them ideal models for the study of many important physical phenomena. The carrier concentration in low-dimensional systems can be controlled by simply changing the bias conditions. This makes them more suitable for use in a wider variety of experiments than bulk semiconductors [4]. The low dimensional carrier systems are excellent models for verifying some of the interesting physical theories like the many body effect, the Quantum Hall Effect etc.

The low dimensional systems have important technological applications as well, specially in high frequency circuits, because of their enhanced mobility. The quantum confinement of the carriers spatially separates them from their respective impurity ions in the barrier region and helps in suppressing ionized impurity scattering in reduced dimensions. The low dimensional systems are therefore characterized by higher mobility of the carriers than in the bulk. Advances in fabrication technology have made it possible to realize high quality low dimensional carrier systems supported by heterostructures. Devices thus fabricated have high switching speeds exceeding orders of trillions of a second. These
devices are known as Modulation Doped Field Effect Transistor (MODFET) or High Electron Mobility Transistor (HEMT) [11,12,16,17]. Beside the high switching devices, the optoelectronic property of the low dimensional systems have been used in developing devices like the Stark Effect Modulators, Infrared detectors etc. They are also used in Quantum Well lasers where there is better confinement of the electromagnetic waves and leakage of the carriers from the active regions is prevented due to the refractive index step.

1.2 Motivation of the Thesis

The two- and one-dimensional electron gas systems have been studied extensively [1-3,13-15] and their physics is well understood [4,15-20]. The two-dimensional hole gas on the other hand is relatively unexplored due to the complex valence band structure [21-24]. Investigation of the properties of the low dimensional holes is very important as it might provide an insight into the understanding of the anisotropic valence band structure. The effective mass of the holes, confined in one or two directions, depends on the growth direction and is different from the bulk value [21]. This further complicates the matter. Hence efforts are being made to understand the physics of the low dimensional hole systems [25,27-30].

Walukiewicz, Manzini et al [2,25,26] have studied scattering mechanisms in a two-dimensional hole gas confined in a p-type GaAs-AlGaAs heterostructure. The two-dimensional hole effective masses have been theoretically calculated by Ekenberg and Altarelli [27,28] and the experimental values of the two-dimensional mobility have been provided by Reemtsma and Hemme [29]. The studies by these workers have shown that an anomaly exists in the determination of the effective mass values of the two-dimensional hole gas present in the p-type GaAs-AlGaAs heterojunction. This is the most commonly used material pair. Thus anomaly has been resolved in this thesis by studying the transport properties of the two-dimensional hole gas in the GaAs-AlGaAs heterostructure and comparing theoretical values with experimental results.
The study of thermoelectric power is important for device characterization. It helps in providing an insight into the various scattering processes operative [34,35] as well as the carrier phonon coupling. Mobility provides a limit to the operating speed of the semiconductor devices. Hence, the relative importance of the different scattering mechanisms must be studied in order to optimize the performance of the devices. The contribution of the carriers to the thermopower resulting from their thermal diffusion is the diffusion thermopower. It gives a better understanding of the various scattering processes operative and their relative contributions at different temperatures. Thermopower due to the energy transfer from phonons to the carriers gives the phonon drag thermopower. The phonon drag thermopower usually dominates at higher temperatures and determines the coupling between the carriers and the phonons. Thermopower measurements at higher temperatures may provide means for determining the exact values of many important parameters like the deformation potential constant for acoustic phonon scattering, phonon mean free path, etc. The values are not yet known accurately [34]. Therefore, the study of both diffusion and phonon drag thermopower is important and has been taken up in this thesis.

Characterization of the semiconductor heterostructures is of utmost importance in connection with device design. Hence, it is an interesting subject to study. Characterization helps in the determination of charge and doping profiles of heterostructures. The energy band discontinuities at the interface which determine its transport and optical properties and hence the overall device performance must also be determined accurately if a heterostructure is to be utilized for an advanced device. Bulk analysis has so far been the prevalent method for studying carrier distribution profiles [36] and to map the doping pattern from Capacitance-Voltage (C-V) measurements. But, the three-dimensional analysis [37] does not hold for a low-dimensional system. In a low-dimensional system, the quantum confinement of the carriers adds a different dimension to the analysis when exposed to an external field [38]. Previous three-dimensional models [36] are not successful in explaining the experimental carrier profiles obtained from C-V...
A quasi two-dimensional model has been developed in this thesis to account for the quantum confinement and field dependence of the carriers. Anomalous experimental finding of an experimental scientist Tittelbach-Helmrich [36] has been successfully explained by this quantum mechanical model proposed in this thesis.

A new and simple method for determining the conduction band offset in a quantum well has been proposed. The method utilizes (C-V) measurements. Since C-V data for p-type semiconductors was not available, the method was applied to directly obtain the conduction band offset of an n-type GaAs-InGaAs quantum well for which experimental data was available. The method can be applied to p-type quantum wells to measure the valence band offset as well.

1.3 Organization of the Thesis

The thesis has been divided into seven chapters. The first chapter gives a brief introduction to the thesis and elaborates on its importance by highlighting its scope and motivation. The physics of heterostructures has been discussed in the second chapter. The third chapter deals with the study of the various scattering processes operative in the two-dimensional hole gas, specifically for the popular GaAs-AlGaAs system. In the fourth chapter, thermoelectric power of a two-dimensional hole gas in an AlGaAs-GaAs heterojunction has been studied in detail. The fifth chapter describes the theoretical model proposed for understanding and explaining anomalous carrier profiles in a p-type Si/SiGe quantum well, Si-SiGe being another popular semiconductor pair. A new method for the determination of the conduction band offset in a quantum well has been given in the sixth chapter. The seventh and the last chapter concludes the thesis by giving a summary of the findings, their implications and possible scope of future studies.
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