CHAPTER I

CHAPTER I

INTRODUCTION

The fast development in the field of semiconductor devices and integrated circuits[1-5] during the last two decades has revolutionised the hardware concept of electronic systems. The range of semiconductor devices has now been extended to millimetre and optical frequencies. ICs have seen a phase transition from LSI to VLSI. This tremendous advance has been made possible by the untiring efforts of researchers all around the world to invent new devices and circuits concept, develop computer-aided modelling techniques for modified device structures, find out new materials with improved properties and establish advanced process technologies.

Of the two important classes of integrated circuits developed so far, MOS-ICs have emerged as more attractive and useful than bipolar ICs because of inherent advantages, such as higher packing density and fabricational yield, inherent memory storage and functional complexity. The charge-coupled device (CCD)[6], introduced in 1970 - a new addition to the MOSLSI family, created a strong impact in the field of signal processing, memory and imaging. Functionally, a CCD is similar to a bucket-brigade device (BBD)[7], but is much simpler, more compact and has other superior features. CCDs have received much attention during the last decade. Theoretical analyses and experimental studies have resulted in realisation of CCDs with improved structures which yield higher charge-transfer efficiency and signal-handling capacity, and lower noise. IC chips including CCDs and peripheral circuits for various applications, such as analog signal processing[8] using transversal filters, memory circuits[9] and optical imagers[10] are now commercially available.

A big step-forward in the CCD development was the advent of buried-channel charge-coupled device (BCCD)[11]. The problems arising from the interface states in the surface-channel device (SCCD) have been eliminated to a great extent in the BCCD in which the channel is shifted away from the interface into the bulk semiconductor by growing an oppositely doped layer adjacent to the interface. This leads to an overall improvement of performance excepting for the deterioration of the signal-handling capacity. Extensive studies have been carried out to realise BCCD with optimum characteristics[12].

The semiconductor material used widely for making discrete devices and ICs is silicon which is an indirect bandgap semiconductor with a relatively low electron mobility (1200 cm^2/V-sec). For high-speed logic and microwave applications, a semiconductor with a higher carrier mobility is desirable. On the other hand, optical band applications prefer a direct bandgap semiconductor. Gallium arsenide - a III-V compound semiconductor which has a direct bandgap of

1.43 eV and a carrier mobility of 8000 cm^2/V-sec, is an excellent choice for both millimetre and optical frequencies. Added with other advantageous features, GaAs is now the most extensively used material for making microwave and optoelectronic devices and circuits. The search for exotic materials with improved properties has brought forth various ternary and quaternary compound semiconductors, such as $Al_cGa_{1-c}As$, $GaAs_cP_{1-c}$, and $Al_{c_1}Ga_{1-c_1}As_{c_2}P_{1-c_2}$, the properties of which can be controlled by adjusting the stoichiometric ratio. Such materials have found vast applications in LEDs, lasers, high-efficiency solar cells, photodetectors and optical integrated circuits[13].

Heterojunctions of two different semiconductors are increasingly used in optoelectronic devices for selective absorption of light and beam confinement. The various processes which have been developed for the growth of heterojunctions are vapour and liquid phase epitaxy (VPE/LPE)[14], molecular beam epitaxy (MBE)[14], metal-organic chemical vapour deposition (MOCVD)[15] etc. Abrupt heterojunctions - both isotype and anisotype, have been studied earlier extensively. Graded heterojunctions in which the composition of the constituent elements is varied gradually across the junction have, however, not been studied in detail. A graded heterojunction is free of interface states and is advantageous in many other respects. Graded heterojunctions have many potential applications which are still to be explored.

The work presented in this dissertation is concerned with two topics: (a) charge-coupled and long-channel MOS devices and (b) graded heterojunctions and their applications.

Chapter II commences with a short review of the evolution of charge-coupled devices. The main problem which has been investigated in detail in this chapter is to find technique to improve the charge-carrying capacity of BCCD. For this purpose, BCCDs with various channel doping profiles are analysed with the help of a computer-aided iteration process. Stepped doping profiles with a peak inside the channel layer are found to yield higher signal-handling capacity compared to uniform and Gaussian profiles of impurity distribution in the channel[16]. The methods of calculation and computed results for potential and field distributions, single carrier transit time and lateral field profiles at different instants of time for realistic clock-pulse waveforms, are presented. This chapter also includes the results of some studies of CCDs with heterostructure with a view to improving optical response and speed for imaging applications.

Chapter III concentrates mainly on the transient behaviour of long-channel MOSFET with segmented gate structure which is analogous to CCD tapped delay line. The turn-on and turn-off characteristics are obtained by solving the nonlinear transmission line diffusion equation appropriate for MOS. Different computational techniques adopted to obtain a good agreement with the available experimental results have been described. A charge-control method to find out the transient charge distribution in CCD is also presented.

Chapter IV is concerned with transport properties and applications of graded heterojunction. In devices employing graded heterojunctions, the bandgap parameters and optical parameters are all dependent on position. The variation of these material properties results in important deviations in device performance. A computer simulation study has been made to find the bandgap, mobility, effective mass and electron affinity of ternary III-V compounds, such as $In_cGa_{1-c}As$, $Al_cGa_{1-c}As$ and $GaAs_{1-c}P_c$. The transport properties of a graded bandgap device have been discussed and the current equation applying to the flow of minority carriers in a graded junction has been developed. This is used to derive the voltage-current (V-I) relation and excess carrier concentrations in a graded bandgap diode assuming a macroscopic slow variation in composition that can be approximated by a position dependent unit cell. As the variation of bandgap causes a variation of dielectric constant, capacitance-voltage (C-V) characteristics depend on the profile of both the doping density and the dielectric constant. The C-V characteristics have been computed for a few composition profiles using a semianalytic method. The presence of internal electric field plays an important role in controlling the performance of a graded diode and transistor, in particular the transit time and alpha cut-off frequency. This has also been discussed in this chapter.

Chapter V presents the results of some studies on heterojunction solar cells. In general, homojunction solar cells exhibit high efficiency, but particularly in direct bandgap material with high absorption coefficient, there are appreciable losses due to front surface recombination which reduce the overall conversion efficiency. This may be avoided in a heterojunction consisting of two different semiconductors providing a wide bandgap window and a narrow bandgap absorber[17]. Unfortunately, because of mismatches in lattice constant and other parameters there is a considerable amount of interface losses. Both the front surface and interface losses can be reduced in a buried homojunction consisting of a p-n homojunction with an additional heteroface junction with a large bandgap semiconductor acting as the window layer[18]. Best efficiencies are obtainable when the window material is properly graded to provide a built-in electric field. A computer analysis of graded heterojunction solar cells has been performed and presented. The first step in the simulation consists of finding the generation rate for a given composition making use of optical absorption coefficient, the characteristics of antireflection coating and incident photon density. The current and continuity equations for graded structure have been formulated and solved iteratively to compute the V-I characteristics. Computations have been made of the efficiencies of some typical structures: (p)GaAs-(n)GaAs; (p)$Al_cGa_{1-c}As$-GaAs-(n)GaAs; (p)$Al_cGa_{1-c}As$-GaAs-(n)GaAs-$In_cGa_{1-c}As$; (n)CdS-(p)Cu_2S; (n)$Zn_cCd_{1-c}S$-CdS-(p)Cu_2S; (n)$Zn_{.3}Cd_{.7}Te$-CdTe-(p)CdTe-Cu_2Te; and (n)$Zn_{.3}Cd_{.7}Te$-CdTe-(p)CdTe-$Cd_cHg_{1-c}Te$.

The velocity profile in the drift region for a microwave transit time device in relation to the velocity in the injection region has an important role in determining the efficiency and the impedance-frequency characteristics[19]. The possibility of using a graded bandgap heterostructure for increasing the efficiency of a Read type IMPATT utilising velocity profiling has been investigated and described in Chapter VI.

The high frequency negative resistance diode, in particular the IMPATT, has been the subject of intensive development for the last decade. This has resulted in realisation of Read type IMPATT device structures providing dc to rf conversion efficiency over 35 per cent[20,21]. It has, however, been realised that a single material IMPATT is unable to meet all the requirements in achieving high efficiency. A two-velocity heterostructure IMPATT where the velocity in the drift region is higher than the entry velocity was proposed[22]. The problem encountered in these abrupt heterojunctions is that special low temperature fabrication technique must be employed and the devices suffer from degradation due to interface states causing a reduction in efficiency. The structures proposed in the present work consist of a low bandgap semiconductor in the avalanche region and graded material in the drift region with a velocity profile shaped to optimise the current conversion ratio. The expected velocity-field and ionisation characteristics of ternary III-V compounds have been found. The ionisation energy, A and b coefficients of ionisation rates and Baraff parameters have been computed for GaAs based ternary alloys using the available experimental results. The efficiencies for different structures have been computed and the results are discussed.

The effect of velocity grading on small-signal impedance-frequency characteristics of an IMPATT having a wide avalanche region, is examined in Chapter VII. Coupled equations for the electric field and difference of electron and hole current densities, which resemble transmission line equations are solved to find the impedance-frequency characteristics of multilayer structures. The structures considered include those with (a) a monotonically increasing velocity profile and (b) profile with a low velocity in the junction region.

Main results of the work are summarised in Chapter VIII where the scope of further work is also discussed.