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Some New Developments in Semiconductor Structures

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Abstract. Some of the recent developments in the field of semiconductor devices are discussed. Two trends are apparent in this area of work. One is the continuous refinement of processes and instruments which enables us to design and fabricate devices in ever smaller dimensions. The second is the study of new structures which are now made possible by such advances in instrumentation and materials technology. New devices based on quantum well structures, superlattices and bandgap engineering are briefly discussed.

1. Introduction

With the development of material technologies such as Molecular Beam Epitaxy (MBE) and Metal-Organic Chemical Vapour Deposition (MOCVD), it has been possible to synthesize and deposit single crystal layers of semiconductors with desired properties and with thickness and uniformity control down to angstrom levels. This unique development has made it possible to observe the effects of quantization of electronic properties in one dimension when the dimensions of the films become small. Periodic spatial modulation is also possible leading to a superlattice. The early development of close confinment double hetero-structure laser diodes in which a thin layer of GaAs is surrounded on either side by layers of Ga$_{1-x}$ Al$_x$As had shown considerable improvement in laser efficiency arising out of confinement of both photons and charge carriers in the central layer. As the thickness of the central layer is decreased and ultimately becomes of the order of the Fermi wavelength $2\pi/k_F$ or $\lambda \simeq h/p$, confined particle or quantum size effects begin to manifest themselves and the structure is called a quantum well (QW) structure. When many such quantum wells within barrier layers are formed sequentially on a substrate, one then has a superlattice (SL). Such QM or SL structures exhibit various fundamental phenomena.

2. Energy Levels

The energy levels of carriers confined in a quantum well or a superlattice can be described in the effective mass approximation by

$$E = \frac{\hbar^2}{2m_z} \frac{\pi^2 n^2}{L_z^2} + \frac{\hbar^2 k^2}{2m}$$

where L_z is the width of the quantum well.

The properties of the carriers could still be considered on the above simple effective mass approximation provided the barrier walls and the quantum well materials have properties of energy band that are not too different. If, however, the barrier layer properties differ significantly from that of the quantum well material, then the analysis becomes more difficult. In the case of the InAs-GaSb superlattice, for example, it has been found that the superlattice behaves like a semi-metal when the superlattice layers are thick, and semiconducting when they are thin.

3. Optical Properties

In this section some of the developments in such structures will be reviewed. The laser emission phenomenon in a QW structure is significantly different from that in ordinary structures. Some of these are : (1) an improvement in the temperature dependence of the threshold current density, (2) improvement in the density of states near the band edge, and (3) lasing at a phonon side band of the electronic transition. In addition, in a conventional GaAlAs-GaAs diode laser, the highest energy of recombination is obtained with the $Ga_{1-x}Al_xAs$ composition near the direct-indirect transition viz. $x = 0.4$, It has been proposed that a QW heterostructure or a SL structure with high barrier layers $x \geqslant 0.75$ and with lowest possible x in the QW layers ($x \leqslant 0.1$) will be a better choice. Experimentally, this state of the art GaAs laser diodes based on multiple quantum well structures has shown continuous emission in the visible region at room temperature with power outputs greater than a Watt.

Since the hydrogenic levels of electron-hole pairs are deeper in a two dimensional case than in the case of three dimensions, excitonic effects are expected to be important in quantum well and superlattice structures. Pairing between spatially separated electrons and holes can lead to excitonic superfluid state—a new mechanism for super-conductivity. Photoluminescence, laser emission and resonant Raman scattering techniques have been employed to study the electronic energy levels in quantum wells.

4. Phonons

Phonons in spatially confined structures in a superlattice have been the subject of intensive investigation. Some new phenomena which do not have a counterpart in three-dimensional structures have been conjectured. Some of these are : (1) The Rayleigh waves, propagating along the surface of a superlattice where the periodic superlattice planes are perpendicular to the direction of propagation, show a dispersive character unlike that on the surface of a homogeneous medium. The dispersion is a function of the number of layers, their thickness, and their elastic properties, (2) Umklapp processes become more important in SL structures when propagation perpendicular to the periodic structure is considered as phonon frequencies required to activate Umklapp processes become smaller, and (3) Evidence of selective absorption of phonons whose wavelength is twice the superlattice period.

5. Transport Properties

There was speculation about the existence of Bloch Oscillations i. e., oscillations in a system in which a charged carrier moves in a spatially periodic potential with a period L_z. The frequency is related to the electric field E by $\nu_B = qL_zE/h$, provided that the relaxation time τ for scattering of the carriers is long enough i. e. $\nu_B\tau \geqslant 1$. Above a threshold field, strong negative differential resistivity appears which leads to the possibility of high speed devices and millimeter wave oscillators. However, this conjecture of Bloch Oscillations is yet to be realized in practice.

Coulomb scattering by ionized impurities could be reduced by confining the dopants in the barrier layer while the carriers tunnel into the active lower band gap layers. This method of modulation doping has shown very high mobilities in GaAs-GaAlAs structures. Such modulation doped devices have shown promise as fast devices which are next only to Josephson devices in their performance levels.

Magnetotransport experiments such as Shubnikovde Haas Oscillations, Cyclotron resonance and magneto-phonon (Gurevich-Firsov Oscillations) effects have been observed in two dimensional structures.

6. New Device Structures

With the possibility of compositional variation during MBE or MOCVD deposition of thin layers, various new superlattice structures have been proposed which have promise in device applications. Band gap engineering has thus become realistic with these structures. Some of the new schemes proposed are: (1) Low noise avalanche photodiodes made possible because of enhancement of electron-hole ionization rates ratio by spatially separating the carriers in different bandgap regions, (2) Staircase photomultiplies where electrons gain energy by band edge discontinuity,(3) Lateral superlattice structures (LSL) for generation of mm waves, and (4) Multilayered heterostructure transit time devices for mm wave generation.

It is thus seen that new developments in material technologies and fine dimension photo-lithography coupled with availability of ultrapure metal-organic compounds have opened up an exciting field of research in electron properties in two-dimensional and superlattice structures. It has been possible to design and develop new structures for specific device functions based on theoretical modeling of electron transport in such two-dimensional and superlattice structures.

References

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