CHAPTER 8

SUMMARY AND FUTURE TRENDS

Abstract

The field of condensed matter physics has witnessed a revolution in the recent past through the invention of semiconductor nanostructure devices. In this chapter, a summary of the important results obtained in the present work on 3D, 2D, 1D and 0D semiconductor systems is given. A few possible future trends of research on the topics of investigation in the present thesis are projected.
I. Summary

I.1 Donor ionization energies and the central-cell corrections

The effective mass approximation is expected to be adequate for the description of donor states in GaAs which has a direct bandgap. Complexities due to inter-valley effects do not arise. Still the theoretical donor ionization energies do not reflect species dependence. To account for this chemical shift, a central-cell short range potential with two parameters for each donor was assumed. The fixation of the parameters and the contribution of central-cell effects have all been described in Chapter-2. The important results obtained are

(i) the central-cell corrections increase with the magnetic field,

(ii) the polaronic shifts obtained using the formula derived from the perturbation theory [1] shows that the shifts are not only small, but also become insignificant in intense magnetic fields (this is attributed to a softening of the electron-LO phonon coupling[1]) and

(iii) the deformation corrections which arise due to the difference in radii between the host and the impurity, worked out within a simple model, give results in agreement with the results of earlier investigators[2,3]. The present results also show that the deformation correction increases with impurity concentration.
I. 2. Photoionization of a donor impurity in a quantum well in an electric field

Photoionization of impurities in GaAs/Ga$_{1-x}$Al$_x$As quantum well systems in the presence of an external electric field is presented in Chapter 3. The important results obtained are

(i) the cross section goes through a peak at a particular photon energy and the peak shifts to a lower energy in an electric field,

(ii) unlike the cases reported in the literature, an enhancement in the cross section values is observed where the confining barriers are infinitely deep (this is attributed to the choice of the trial function used in Ref.[4] and due to tunneling effects) and

(iii) the behaviour of photoionization cross section with energy is different in the two cases- the radiation is z-polarized (growth direction) or polarized in the x-y plane.

I.3. Acceptors in semimagnetic quantum well systems

Binding energy of a shallow acceptor in an isolated quantum well of a semimagnetic quantum well system is discussed in Chapter 4. Contrary to the general understanding that the band discontinuities may be worked out using the Zeeman splittings of the split-off J=3/2 valence band [5,6], the experimentally observed critical magnetic fields at which the type-I to type-II transition occurs do not follow from these splittings [5]. An empirical formula is suggested for the (Eq.(2) of Chapter 4) estimation of the barrier heights for any magnetic field. The variation of the barrier height with magnetic field leads to observable changes in all the observed physical
properties of DMS quantum well systems. The important results obtained are

(i) the barrier height decreases in a magnetic field,

(ii) the acceptor ionization energy goes through a peak, with the peak value occurring for a well width 20 Å (for the CdTe/Cd$_{1-x}$Mn$_x$Te with x=0.3),

(iii) the magnetic field enhances the ionization energy,

(iv) the photoionization cross section behaves in a similar way with the incident photon energy for x- and z-polarized light, and the magnetic field enhancing the cross section in the z-polarized case, and

(v) carrier capture time increases in a magnetic field though the variation is not appreciable, only 3%. In the calculation of carrier capture, the effect of confined phonons have been taken into account following Weber et al.[7]. Some of the results that are in variance with similar works in the literature are explained in Chapter-4.

I. 4. Carrier transport in a QWW and distribution dependence

Following the simple model given by Lee and Spector for a cylindrical wire, carrier transport properties and their dependence on different forms of impurity distribution are presented in Chapters 5 and 6. Effects of temperature, pressure, electron-phonon interactions and dielectric screening have all been investigated in this simple model. The important results obtained are

(i) mobility values increase with temperature,

(ii) carrier mobility increases with the radius of the wire,
(iii) polaronic shifts neither alter the shape nor the values of mobility appreciably (the maximum change is about 10%),
(iv) screening effects are negligible for wires of radii larger than 100 Å and
(v) mobility values are affected by the choice of the impurity distribution function.

I. 5 Donor binding energies in a spherical quantum dot

Effects of electric field and hydrostatic pressure on donor binding energies in a spherical quantum dot with parabolic confinement have been investigated in Chapter 7. The important results obtained are
(i) the ionization energy decreases when the dot radius increases going through a peak in a finite barrier problem,
(ii) the ionization energy increases with pressure,
(iii) the ionization energy reduces in an electric field, and
(iv) the screening effect is appreciable only for small dots.

These results are discussed in the light of the existing literature (see Chapter 7).

II. Projected future trends

a. Impurity states in many valley semiconductors

1. Proper many valley theory

The Kohn-Luttinger effective mass theory has been used in the study of impurity states in Chapter 2. As remarked earlier (see Chapter 1), this theory is not correct for semiconductors like GaP, Si, Ge etc. which exhibit
equivalent conduction band minima. In the absence of a proper theory that
takes into account the many valley effects, the KLEMT is used to obtain the
order of magnitude estimates of the donor ionization energies. The KLEMT
is adequate for the excited states.

The major theoretical problem is the proper inclusion of the inter-
valley terms in the effective mass equation. This remains as an unsolved
problem for more than five decades. It is suggested that an approach similar
to the renormalization group method [8], wherein in every iteration
interactions drop out leading to the critical point, will be a good solution to
the problem. A similar procedure when applied to donors in a many valley
semiconductor should drop certain inter-valley terms on every iteration
leading to a final effective mass equation wherein the inter-valley terms are
properly included.

2. Strain correction

The mechanical effect of inserting an impurity at an interstitial site of
a semiconductor produces strains in the lattice that affect the impurity
binding energies as explained in Chapter 1. However, a theory showing how
this effect varies with distance is not available. When it becomes available,
this will also be used as a potential in the effective mass theory.

b. Low dimensional semiconductor systems

A new field called ‘spintronics’ is drawing considerable attention at
present [8a,8b]. This field is supposed to revolutionize electronics. Here one
exploits the spin of the electron rather than its charge. A single spin is
considered as the ultimate limit of information storage. Some new quantum devices which may emerge in future are

(i) spin quantum computers [9],
(ii) spin memory devices [10],
(iii) spin transistors[11],
(iv) spin filters and modulators, etc.

Most of the proposed spintronic devices involve spin polarized transport across interfaces in various hybrid structures such as magnetic tunnel junction[12], DMS heterostructure[13], ferromagnetic semiconducting heterostructure[14], and semiconductor-superconductor hybrid structures[15]. Theoretical studies on these emerging areas will be of great interest in the near future.

c. Spin glass-antiferromagnetic transition in DMS

Only recently the problem of the phase transition from spin glass to antiferromagnetism in DMS epilayers such as Cd$_{1-x}$Mn$_x$Te, Zn$_{1-x}$Mn$_x$Te etc. as a function of the magnetic ion concentration has drawn the attention of scientists working on DMS [16,17]. Such studies will throw light on the position of the critical magnetic field at which type-I to type-II transition occurs. Further, such studies are also significant in the general context of phase transition in lower dimensions. Recently metal-insulator transition has been observed in a 2DEG system [18] for which no clear-cut theoretical explanation is available at present. Such a transition is in contradiction with the scaling theory of phase transition [19].
**d. Relativistic effects**

For a hydrogen atom in 2D, the ionization energy is 4 Rydberg. Confinement increases the energies of electrons and phonons. The electron-phonon interaction is also enhanced in lower dimensions (see Chapter-1 for polaronic effects). Hence the relativistic effects should manifest in several properties of LDSS. Only recently some efforts have been made to estimate a few relativistic effects like the spin-orbit energy [20]. For instance, how the relativistic effects manifest in transport properties like the carrier mobility have not been addressed. In a simple calculation an expression for the relaxation time for a carrier in a QWW has been obtained [21] as

\[
\tau^{-1} = \left( \frac{N_1 m \pi}{2} \right) \left( \frac{Ze^2}{2\pi e} \right)^2 \left\{ \frac{1}{\hbar^2 k^2} + \frac{\hbar c^4}{(E + mc^2)^4} - \frac{2c^2}{\hbar k(E + mc^2)^2} \right\}^{\frac{1}{2}} \left[ K_0^2(2kd) - K_1^2(2kd) \right]
\]

where \( N_1 \) is the density of ionized impurities, \( c \) the velocity of light, \( E \) the energy of the particle, \( d \) the radius of the wire, \( \varepsilon \) the dielectric permittivity of the semiconductor, and \( K_n(x) \) are the modified Bessel functions of the second kind of order \( n \). A proper study of the properties of LDSS with relativistic effects should be pursued.

**e. Carrier mobilities-optimising parameters**

A figure of merit of a semiconductor device may be the carrier mobility. One may bring in similarity with a superconductor with a high value for transition temperature. Larger values of both these parameters are welcome for technological advancement and applications. At present there is no limiting value for \( T_c \) in a superconductor, though experimentally a value around 120 K is the accepted highest value at present. Is there a limiting value for carrier mobility? One of the reasons for the realization of...
LDSS is to separate the carrier from the ionized impurity so as to reduce the ionized impurity scattering and bring about large values of mobilities. At present mobilities in excess of $10^7 \text{cm}^2/\text{V-s}$ are realized. To attain still higher values proper choice of materials is required. Of the several optimizing parameters that control carrier mobility in a quantum well wire, the material parameters like effective mass and dielectric constant together affect the values by one or two orders. This observation will be useful in the fabrication of the wires for applications. The origin of this important observation can be traced to two of the fundamental properties of a semiconductor viz. the lattice constant and the bandgap. These values for InSb and ZnS are 0.26eV, 6.48Å and 3.7eV and (approximately) 4Å respectively. It is known that while the Penn model gives $\varepsilon = 1 + \left( \frac{\hbar \omega_p}{\varepsilon_g} \right)^2$ where $\omega_p$ is the plasma frequency and $\varepsilon_g$ is an average gap, the effective mass is given by $m^* = \left( \frac{2}{m a^2 E_g} \right)^{-1}$ where $a$ is the lattice constant. Hence $\left( \frac{\varepsilon}{m^*} \right)^2$ is proportional to $(E_g a^4)^{-1}$. Thus the mobility ($\mu$) obtained from Eq.(3) of Chapter 5 for InSb is large as compared to ZnS (see Table 1).

f. Role of impurities in carbon nanotubes

At present there has been world wide interest on carbon nanotubes due to their strong mechanical properties[22]. Both in the armchair and zig-zag configurations, the effect of impurities have not been pursued. Such studies may become useful when carbon tubes find wide applications in hitherto unknown areas.
TABLE 1 Mobility values of a few semiconductors –optimising parameters

<table>
<thead>
<tr>
<th>Semiconductor</th>
<th>$\varepsilon$</th>
<th>$\frac{m^*}{m_0}$</th>
<th>$\mu$ (cm$^2$/V-s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>InSb</td>
<td>17</td>
<td>0.013</td>
<td>78,000</td>
</tr>
<tr>
<td>ZnS</td>
<td>8</td>
<td>1.1</td>
<td>165</td>
</tr>
<tr>
<td>GaAs</td>
<td>12.4</td>
<td>0.067</td>
<td>8500</td>
</tr>
</tbody>
</table>
g. Biexciton and exciton complexes

Though some recent studies have been directed towards observing and understanding the formations of biexcitons and exciton complexes in LDSS[23], the interaction among them leading to an excitonic liquid, exhibiting Bose-Einstein condensation, has not been attempted. Again, such studies will throw light on the nature of phase transition in lower dimensions.

h. Applications in devices

Already QW and QD lasers are realized. A few other promising areas of application are fast optical switching and waveguides, high efficient emission of radiation and lasing with tuneability over a wide spectral range and microelectrodes and photo-catalysts in photochemical reactions. There appear to be no limits to the realization of new effects on the optical applications of QW and QD devices.

i. Superconductivity

In a bulk semiconductor Cohen[24] and Rasolt [25] have predicted superconductivity. Rasolt has shown the possibility of superconductivity in a many valley semiconductor in a strong magnetic field ! Since the electron-lattice interaction is enhanced, the possibility of studying superconductivity in LDSS may be worthwhile. It is to be remarked that high \( T_c \) superconductors, based on oxides, also exhibit layered structure. Such studies will also throw light on the possibility of phase transition in dimensions less than three.

The other relevant references are given as Ref.[26-30].
References


(The above two references contain information on cyclotron resonance experiments on exited states)