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Quantum wires, quantum boxes and related structures: Physics, device potentials and structural requirements

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Unique features of quantum wires (QWI), quantum box (QB), and related structures are discussed to clarify those physical processes that can be exploited for the creation of advanced device functions. We review first various schemes to suppress scattering processes by impurities, interface roughness, phonons, and electrons in these structures. Then, the advantage and limitation of gate-controlled planar superlattices and other quantum interference devices are examined. Physical basis for the advantages of using QWI/QB structures as optoelectronic materials is also discussed. Finally, structural requirements to obtain these desirable properties are clarified.

1. Introduction

For the last two decades much work has been done on electronic properties of ultrathin semiconductor heterostructures. When the thickness L_z of such a film is of the order of 100 Å, electron energy for the motion normal to the layer is quantized to a series of discrete levels $E_z(1)$, $E_z(2)$, ... while the electron motion within the (x, y) plane remains free, as depicted in fig. 1a. Unique features of such two-dimensional carriers have been disclosed and some of them have been exploited to create such advanced devices as resonant tunneling diodes, intersubband photodetectors, Stark modulators, quantum well lasers, and high electron mobility transistors.

It should be noted that majority of quantum phenomena observed in these layered structures persist even at room temperature. This is primarily because the energy spacing between the first and the second level is around 100 meV, which is large enough to surpass the level broadening (1–10 meV) caused by scattering and inhomogeneities and also is wide enough (as compared with the thermal energy kT or the Fermi energy E_F) to prevent the electron population in the

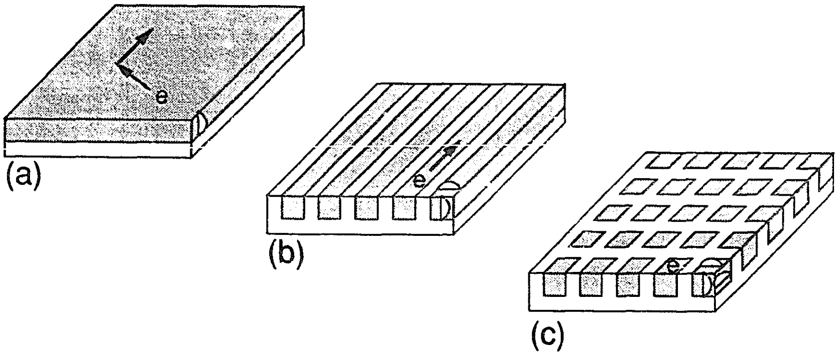

Fig. 1. (a) Schematic diagrams of a quantum well (film), (b) a quantum wire (QWI) array, (c) and a quantum box (QB) array.

excited levels. If the film thickness L_z were increased to 1000 Å, the majority of quantum phenomena would be smeared out unless the measurement is done at very low temperatures in very pure samples, since the level spacing would become of the order of 1 meV.

In an attempt to expand the forefront of research on quantum effects in semiconductor microstructures, the author initiated a theoretical work in 1975 on the possible use of quantum wires (QWI's), quantum boxes (QB's), and planer superlattices (PSL's) for the creation of advanced devices [1]. As shown in figs. 1b and c, the degree of freedom of electronic motion will be further reduced in these structures and a variety of new phenomena are anticipated. Since this work, a number of theoretical and experimental works have been performed and disclosed unique features of these systems. In this paper, we focus our attention to some of those electronic processes which are potentially attractive for device applications and examine their potentials. We briefly discuss also the recent effort to prepare these structures with cross sectional dimensions L_y and L_x of the order of 100 Å.

2. Suppression of scattering rates in single mode quantum wires

2.1. Scattering by impurity and interface roughness

When the cross section of a quantum wire is small enough to accommodate all the electrons in the ground subband, electrons move freely only along the wire as shown in figs. 2a and b. The author has examined elastic scattering processes in such systems and has shown theoretically that an electron with wave number k_f can be scattered nowhere except the state with wave number of $-k_f$, as illustrated in fig. 2c [2]. Since this backward scattering requires a large change of momentum $\Delta k = 2k_f$, its probability is expected to be small. It is particularly true when the Fermi wave number k_f or the electron concentration n_e is high. Hence, the low temperature mobility limited by ionized impurities (II) is expected to be extremely enhanced; for example, the II-limited mobility in GaAs wire is found to be expressed in the absence of screening simply as 341 $\mathrm{cm}^2/\mathrm{V\,s} \times (n_e d)\exp(2n_e d)$, where d is the distance between the wire and impurities. Hence the calculated mobility reaches as high as $3 \times 10^8\ \mathrm{cm}^2/\mathrm{V\,s}$ when $n_e = 10^6/\mathrm{cm}$ and $d = 200$ Å.

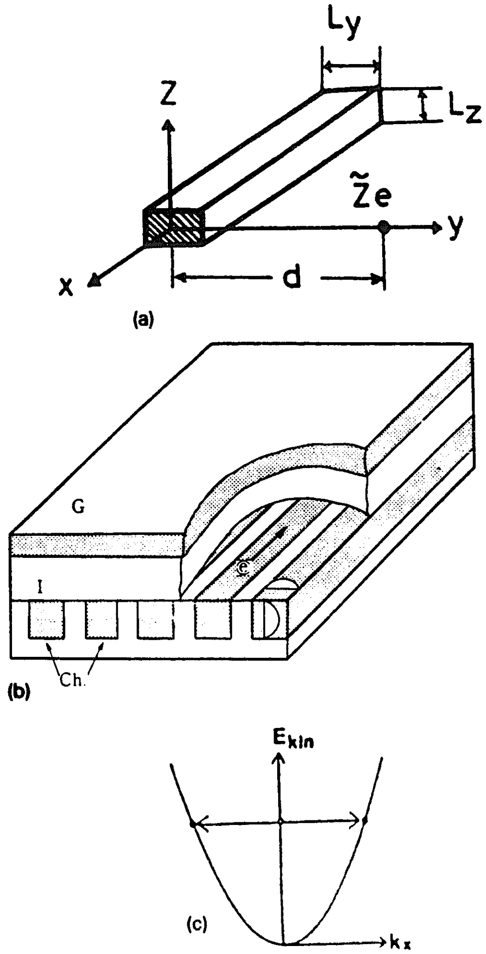

Fig. 2. (a) A single-mode quantum wire and a remote impurity location assumed in the mobility calculation, (b) a schematic drawing of a quantum wire array FET with gate, (c) and the dispersion relation of one-dimensional electrons.

For the same reason, the scattering rate of electrons by interface roughness is expected to be suppressed in a single mode quantum wire. Fig. 3 shows the roughness-limited mobility in a GaAs wire calculated as functions of electron concentration n_e [3]. It is clear that the mobility increases drastically with n_e; this is because the scattering at high n_e is governed by a high frequency component of roughness potential which is known to decrease rapidly as the wave number

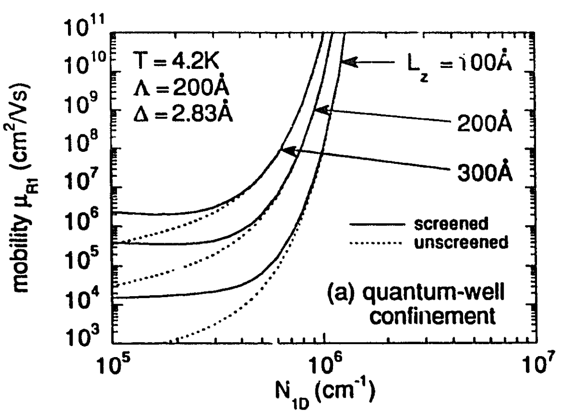

Fig. 3. Roughness-dominated mobility of electrons in single-mode quantum wires with three different wire width L_z plotted as functions of electron concentration N_{1D}. The solid lines and broken lines are those obtained with and without screening. The amplitude and the correlation length of roughness is assumed to be 2.8 Å and 200 Å, respectively.

$q = 2k_f$ increases. This ultrahigh mobility feature of a quantum wire is certainly attractive in such applications as ordinary FET's and quantum interference devices, as will be discussed later.

2.2. *Phonon scatterings and enhancement of saturation velocity*

Usually the electron transport in polar semiconductors is dominated by optical phonon scattering at room temperature or at high electric fields. This is generally true also for GaAs quantum wires and reduces the attractiveness of QWI's as an FET material. However, Yamada and Sone have theoretically found that the optical phonon emission process can be suppressed in single mode quantum wires, and the substantial enhancement of saturation velocities is expected at low temperatures [4]. This attractive feature is predicted when the electron concentration n_e is high enough to bring the Fermi energy E_f above the optical phonon energy (−35 meV). If such an enhancement is indeed achieved, a quantum wire array may provide not only higher mobility but higher saturation velocity. Hence, it may serve as a superior channel material to be used for high speed FET's. Of course, in such applications a few hundreds of parallel wires should be used, as illustrated in fig. 2b, to achieve a reasonable current drive capability(-mA), since each wire carries only a few microamperes of current in the limit of high electric fields.

2.3. *Electron-electron scattering and enhanced coherence length*

A number of works has shown that the dominant phase breaking mechanism of two-dimensional electrons at low temperatures is electron–electron (EE) scattering. This imposes a serious limitation on the use of quantum interference phenomena for practical devices. In a single mode quantum wire, however, because of the one-dimensional nature of k-space (fig. 2c), one would expect the elimination of the first order EE scattering if the spin degeneracy were to be ignored. Indeed, Fasol has recently evaluated the scattering rate with the spin degeneracy being taken into account and has found the substantial reduction of the EE scattering rate [5]. Hence, the single mode quantum wire and its parallel array will be attractive systems in which quantum interference phenomena can be exploited under less stringent conditions. This point will be discussed later in section 4.

3. Phonon scatterings in coupled and uncoupled quantum box systems

It has been pointed out by the author [6] that electron transport in the ground miniband of a coupled quantum box array of fig. 1c or its linear array can be quite different from any other semiconductor structure, since the influence of optical phonon scattering can be almost eliminated if the following three conditions are met as shown in fig. 4a:

(S-1) the first minigap is much wider than the average kinetic energy (E_f or kT_e) of electrons so that electron transport takes place only within the ground miniband;

(S-2) the width of ground miniband is narrower than the optical phonon energy E_{op} (~ 30 meV) so that neither the optical phonon emission nor its absorption is allowed within the miniband;

(S-3) the first minigap is wider than E_{op} so that no inter-miniband scattering is allowed (except through a multiple phonon process).

If the optical phonon scattering is indeed suppressed by this scheme, electrons may exhibit almost scattering-free transport at high electric fields and may well lead to the first realization of Bloch-oscillation and other coherent phenomena even at high carrier temperatures. Note that when the miniband width is 20 meV and the period of a superlattice is 100 Å,the maximum group velocity of electrons can be as high as 3×10^7 cm/s and can supply reasonably large current.

The same mechanism to reduce the electron-optical phonon interaction should work equally in small uncoupled quantum box (QB) structures which have been considered as an attractive material for various optical devices (section 5). This reduction of interaction will have some influences on such QB optical devices. For example, the lifetime broadening of excitonic line caused by optical phonons will be suppressed. In addition, the energy relaxation process of injected carriers from the higher levels to the ground level of the QB will be slowed down; this point was recently pointed out independently by Bockelman and Bastard [7] and by Benisty et al. [8]. For an efficient and high speed modulation of QB lasers and modulators, one must devise an injection method to circumvent this problem.

4. Quantum interference devices: Requirements and prospects

As described earlier, the use of single-mode quantum wires is effective to reduce the scattering rate and prolong the coherence length. This feature is advantageous in realizing any kinds of quantum interference (QUINT) devices, since in these devices the coherent interference of waves is controlled by external signals so as to reduce or increase the electron transmission. The planar superlattice (PSL) FET proposed by the author is the first QUINT device [1] and has the structure exactly the same as multi-quantum wire FET of fig. 2b, except that the current flows normal to the wire direction. A similar proposal was later made for the double-barrier case [9].

This FET makes use of Bragg interaction (diffraction) of electron waves with an in-plane periodic potential $V(x)$. Note that the gate voltage can be used to vary the electron wavelength (through the electron concentration) as well as the miniband structure itself (through the potential). This Bragg interference transistor is predicted to exhibit both gate-controlled negative resistance and negative transconductances. Indeed these features have been demonstrated recently by Ismail et al. [10], who performed an experiment at low temperatures on a special GaAs/AlGaAs heterojunction FET having the PSL potential with the period of 2000 Å. If this period of PSL is set at a few times 100 Å, then the Bragg-reflection operation may persist even at room temperature for the reason discussed earlier.

Another scheme of quantum interference devices was proposed by Datta et al. [11]. It is the electrostatic Aharonov–Bohm FET where the electron waves interfere in a double-path geometry and is to be controlled by gate voltage. This scheme is of course effective only when the electrons maintain their phases and modes. Hence, the use of single mode wire to construct the the double-path geometry is highly desirable.

In order for any of these quantum interference devices to be ever practical, they must satisfy several conditions. Here we discuss only a few of them. The important point is that the phase ϕ or the phase difference $\Delta\phi$ of interfering electron waves must be determined with sufficient accuracy in order to keep the logic error below an acceptable level. The reduction of such phase uncertainty $\Delta\phi$ can be achieved only by flowing a sufficient number N of electrons. Shimizu has analyzed this problem and has shown that N must exceed typically 10 [12]. Hence, to achieve a high speed switching with the typical time constant of τ, the total current of quantum interference devices must exceed qN/τ, which is 1.6 μA if τ is 1 ps.

This means that picosecond switching operation is possible only in those devices that can carry the current of 1 μA or more. Note that this requirement can be easily met by the Bragg-interference transistor, since this allows the parallel flow of current. In contrast, the standard Aharonov–Bohm (AB) transistor of double-path geometry does not meet this condition unless it is substantially modified. It is needless to say that such a high current drive capability is also important in minimizing the charging time of these devices as long as the electrostatic field-effect is used to control the quantum interference.

Another important point is whether or not a voltage gain can be achieved in these devices. To provide the gain, devices at off-state must shut off the current at a reasonably high drain voltage. This requirement can be easily satisfied by the Bragg interference transistor, as long as the superlattice period is short enough to make the minigap sufficiently wide. On the contrary, this requirement cannot be easily met by the electrostatic AB device.

5. Applications for lasers and other optoelectronic device

The use of quantum wires (QWI's) and/or boxes (QB's) in the active region of laser diodes (LD) was first proposed and analyzed by Arakawa and Sakaki [13]. This work and further work on such lasers have theoretically shown that both the threshold current J_{th} and its temperature variation (dJ_{th}/dT) should dramatically decrease, while the high-frequency response (the maximum modulation frequency) should improve by a factor of 3 ~ 6 [14]. These predicted improvements are due mainly to the sharpening of the gain spectrum $g(h\nu)$ or the density-of-states functions of QWI/QB systems (from the quasi-continuum one to a δ-function-like one as depicted in fig. 4b), though some advantages result mainly from the smallness of the active layer volume.

The use of quantum wires and quantum boxes as efficient electro-optic materials has been considered by Miller et al. for the case of the Stark effect [15] and by Sakaki et al. for the case of the carrier-induced bleaching effect [16]. In either case, the real advantages of these systems result from the peaked feature of the joint density of states as in the case of lasers.

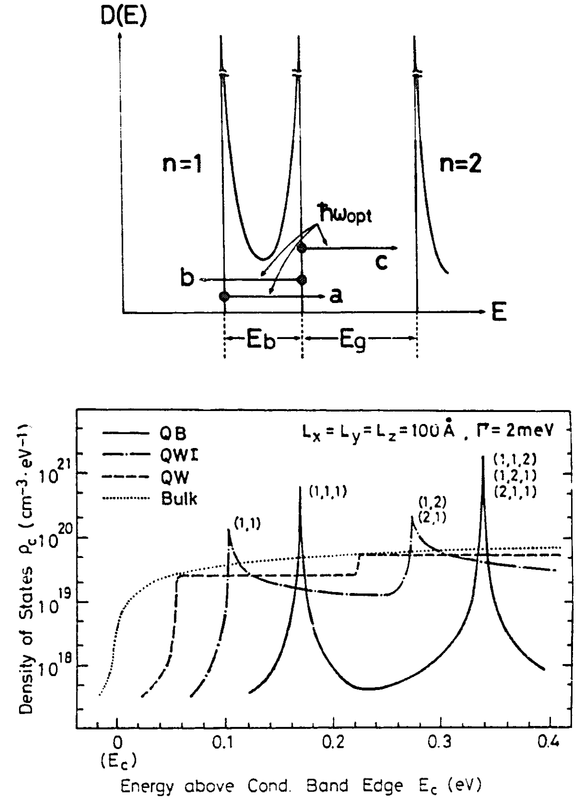

Fig. 4. (a) The density of states (DOS) of electrons in a coupled quantum box structure and (b) those DOS's of a bulk, a quantum well, a quantum wire, and a quantum box system.

Note that the substantial sharpening of the gain and/or absorption spectra can be achieved only when the level separation E(2)–E(1) is far bigger than thermal energy kT or the Fermi energy E_F and the level broadening ΔE(1) is far smaller than kT or E_F, so that all the injected carriers are accommodated in the sharply defined ground level. Note that these are almost the same requirement imposed on transport devices when desirable properties are to be obtained as discussed in section 2, 3 and 4.

6. Conclusion and prospects

From the discussion given up to now, it is clear that the most of drastic physical phenomena and their device applications are to be realized only when the ground quantum level of QWI/QB structures is sharply defined ($\Delta E \ll E_f$, kT_e) and accommodates the major portion of carriers (E(2) − E(1) > E_f, kT_e). Since E_f and/or kT_e of typical devices are of the order of 10 meV under normal operating conditions, it is necessary to set a large energy level spacing (E(2) − E(1) ≫ 10 meV) and a small level broadening (ΔE < 5 meV) at the same time. Hence one must advance the fabrication technology and prepare QWI/QB structures with characteristic length < 250 Å with tolerable geometrical inhomogeneities. While remarkable progresses in lithography are continually made, these dimensions are still quite difficult to handle. Hence, it appears highly desirable to look for various new approaches to prepare such structures.

It has been proposed by Sakaki [2] that a QWI may be prepared by forming inversion layers or the T-shaped quantum well on the edge of multilayered quantum wells as shown in fig. 5a. While the preparation of such structures was difficult because of the Fermi level pinning phenomenon at etched GaAs surfaces, the recent progress in the selective facet growth of quantum well structures and/or the cleavage process followed by the selective growth have nearly allowed the fabrication of such edge wire systems [17–19] as shown in fig. 5b.

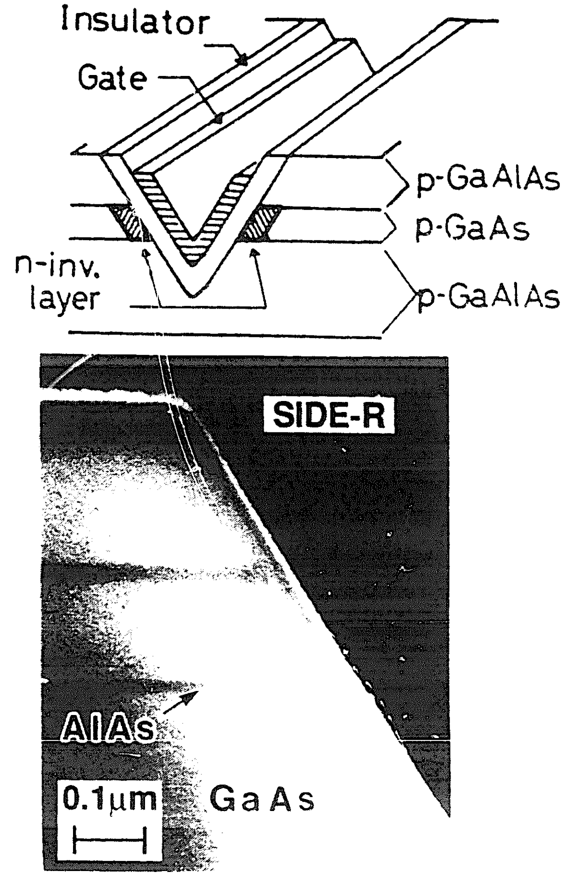

Fig. 5. (a) The concept of an edge quantum wire, where the confinement is done by a heterostructure potential in one direction and by electrostatic field in the other. (b) An example of MBE-grown GaAs/AlAs facet structure is shown.

As the second alternative, Petroff proposed a novel method of depositing half-monolayers of GaAs and AlAs alternately on vicinal GaAs substrates, where quasi-regular steps are expected to be formed [20]. Recent experiments by Fukui et al. [21], Petroff et al. [22] and Tanaka and Sakaki [23] have given positive evidence for the formation of laterally modulated structures, although the composition modulation along the x-axis is still far from perfect. For the substantial improvement of such structures, very detailed work must be done to clarify the incorporation process of atoms at the step edge during the growth.

If the material science of these lateral quantum structures is continually developed, it may open an exciting new field of physics and offer a variety of new possibilities in solid state electronics.

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