Quantum state depression in quantum well devices

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Development of semiconductor heterostructures enables quantum well (QW) devices. QW MOSFET transistors, lasers, and solar cells, are fabricated. Recently, new quantum size effect, quantum state depression (QSD) was investigated both theoretically [1] and experimentally [2] in metal QW. QSD is based on the ridged geometry of QW boundary. The ridges impose additional boundary conditions on electron wave function and some quantum states become quantum-mechanically forbidden. Quantum state density n_S is reduced. Electrons from forbidden energy levels have to occupy higher energy levels and Fermi energy E_F increase. In semiconductor, QSD reduce n_S within of all energy bands and rejected electrons occupy empty levels in empty bands). QSD has the same effect as conventional donor doping. It depends on electron confinement and therefore, is most pronounced in QW structures. For instance, n_S is dramatically reduced in ridged quantum well (RQW) with respect to conventional QW of the same width. This allows fabrication of a wide RQW with quantum properties. As RQW is wider, it becomes possible to adjust it's width, using the charge depletion like in a MOSFET transistor channel. It follows that fabricating of a RQW with tunable energy levels and tunable E_F becomes technologically feasible. Such QRW can be used in the channel of ballistic MOSFET transistor and other QW based devices.

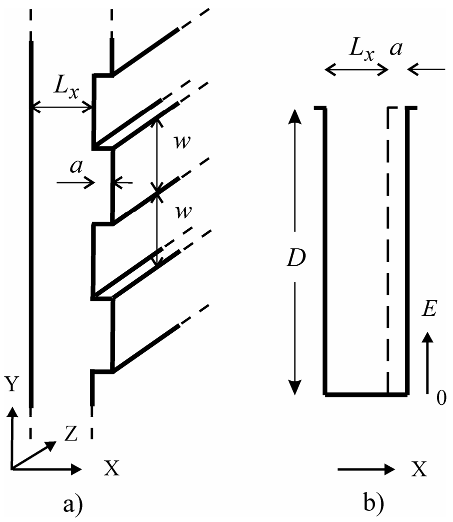

Fig. 1 a) 3D view of ridged quantum well, b) schematic representation of RQW.

Cross section of a RQW layer is shown in Fig. 1a. There are periodic ridges of width of w and height of a on the surface of a conventional QW. Potential energy changes instantly, by value D, at the surface of all of the walls. Fig.1b shows corresponding potential energy well. Dashed line in Fig 1b depicts double boundary. Metal RQW was investigated in [1]. Here we find distinctive features of semiconductor RQW.

As a semiconductor QW is well studied, it is convenient to make the quantitative comparison between a RQW and QW. We express the main parameters such as n_S and E_F of a RQW in terms of the same parameters of a conventional QW (a=0). We assume that both wells are made from the same undoped material and have depths D, high enough to allow approximation of infinitely deep well.

Analysis made on the basis of band theory and within the limit of light doping shows that density of quantum states n_S is reduced by factor $G = L_y(L_x + a/2)/aw$ in RQW relative to QW of the same volume. Electron density in conductance band (CB) of RQW is

$$\mathrm{n}_{\mathrm{RQW}} = \frac{1}{2G}\left\langle n_{\mathrm{CON}}(G-1) + \left[n_{\mathrm{CON}}{}^{2}(G-1)^{2} + 4\mathrm{n}_{\mathrm{QW}}{}^{2} \right]^{1/2} \right\rangle \quad . \tag{1}$$

Here, n_{con} is total density of forbidden states in all energy bands and n_{QW} is electron density in conventional QW. We find Fermi energy increase in RQW with respect to QW

$$\Delta E_{\mathrm{F}} = k_{\mathrm{B}}\, T \ln \frac{\mathrm{n}_{\mathrm{RQW}}}{(\mathrm{n}_{\mathrm{QW}} / G)} = k_{\mathrm{B}}\, T \ln \left\langle \frac{n_{\mathrm{CON}}(G-1)}{2\mathrm{n}_{\mathrm{QW}}} + \left[\frac{{n_{\mathrm{CON}}}^2 (G-1)^2}{4{\mathrm{n}_{\mathrm{QW}}}^2} + 1 \right]^{1/2} \right\rangle . \quad (2)$$

Carrier scattering rates are proportional to $n_{\mathrm{S}}(E)$ according to Fermi's golden rule and reduce in RQW. Scattering rates reduce both for confined electrons and holes. All types of scattering rates including impurity, acoustic phonon and optical phonon scattering decrease $\approx G$ times. In first approximation carrier mean free path l_{tr} enlarge G times.

Conventional QW has quasi-2D structure $L_y, L_z >> L_{\mathrm{x}}$ and no quantum features are considered in Y and Z directions. QW layer has typical thickness of L_x=10 ÷ 20 nm. Not normalized state density $N_{\mathrm{S}}(E) = n_{\mathrm{S}}(E) L_x S$, where S is layer surface. $N_{\mathrm{S}}(E)$ is proportional to the product $n_{\mathrm{S}}(E) L_x$. As $n_{\mathrm{S}}(E)$ in RQW is reduced G times, L_{x} can be increased same G times without loss of quantum properties. Let us find G. There is no analytical solution to the time independent Schrödinger equation in ridged well (solution contains infinite sums), and G can not be found for arbitrary w, a, L_{x} [1]. However, there is powerful software designed for wave mode calculation in waveguides, including ridged waveguides [3]. It could be used to calculate transverse wave vector spectrum and find numerical value of G, for any L_{x}, a, w. We note that, mathematically there is no difference between QSD and electromagnetic mode depression. However, electron falls under Pauli exclusion principle and analogy should be conducted with care.

General requirement for RQW is that $w >> a$ (to avoid de Broglie wave diffraction). It allows assumption that k spectrum is quasi-continuous in Y direction. Then, in first approximation, G could be rewritten in a simpler form

$$G = (L_x + a/2)/a \approx L_x / a . \quad (3)$$

Here we suppose that, $a << 2L_{\mathrm{x}}$ which is satisfied automatically within the perturbation method limit. We think that method is precise enough in the range $5 < (L_{\mathrm{x}}/a) < 10$ and Eq. (3) can be used for that range (method can not be used for $a \to 0$, since wave diffraction leads to ignoring ridges) . Consequently, we will use values of G=5 ÷ 10 for further estimations. It follows that, in practice, 20 nm wide QW could be replaced by 100 ÷ 200 nm wide RQW.

For optoelectronics and power electronics it is important to have suitable wide bandgap materials [4]. Semiconductors with E_{g}>1.5 eV is difficult to utilize as their electrical conductivity is low. Doping is typically used to increase electron concentration in CB. However, conventional doping introduces impurity centers and increases electron scattering. QSD doping can be used to solve the problem. It increases electron concentration in CB without introducing scattering centers. Besides it, QSD reduces scattering rates in both CB and VB. QW embedded in p-i-n junction is frequently used for solar cells [5].Typical QW layer is only 10 ÷ 20 nm thick and there is the light confinement problem. To overcome it, complicated multiple QW heterostructures are fabricated. QSD can contribute in difficulty solving. RQW layer has the same quantum properties at more thickness. This increases light confinement. Reduced number of RQW layers will be needed. Combination of QW and RQW can also be used for solar cells. Here we describe one possible combination. Single QW is embedded inside the RQW. Fig. 2(b) shows energy diagram. For comparison, in the same figure we give energy diagram of QW, embedded inside the conventional QW [Fig. 2(a)]. The QW in QW system has low $N_{\mathrm{S}}(E)$ within the energy range $E_{\mathrm{C3}} < E < E_{\mathrm{C2}}$ (E_{C3}, E_{C2}, E_{C1} are CB bottoms). This is due to low width of internal QW. In the range $E_{\mathrm{C2}} < E < E_{\mathrm{C1}}$, $N_{\mathrm{S}}(E)$

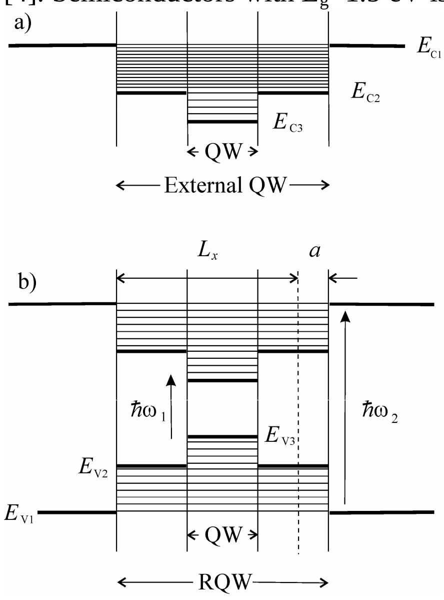

Fig.2 Energy diagrams for a) QW inside the QW, b) QW inside RQW.

is higher as external QW is wider. We replace external QW by the RQW of same width [Fig.2(b)]. Then, $N_S(E)$ reduces due to QSD inside the energy range $E_{C2} < E < E_{C1}$. As result, we get system which has low $N_S(E)$ in broad energy range $E_{C3} < E < E_{C1}$ (same is true for holes in VB). Parameter G can be selected so that, state densities match. Such RQW(QW) heterostructure has quantum properties close to the internal QW. Simultaneously it has same low $N_S(E)$ in broader energy range and is itself wider than internal QW. It has almost uniform $N_S(E)$ over energy range $E_{C3} < E < E_{C1}$. Consequently, broad photon spectrum $\omega_1 < \omega < \omega_2$ can be efficiently converted into electricity. As RQW(QW) heterostructure is wider, it better confines light. It also has higher electrical conductivity due to low $N_S(E)$.

QW is often used for heterostructure lasers [6]. Let us consider p-n-n$^+$ junction laser based on RQW. Fig. 3 shows energy diagram for GaAs RQW hetrostructure. RQW is embedded between p doped AlGaAs and n doped AlGaAs layers. n doped AlGaAs is n$^+$ doped to the depth, not approaching RQW from the right side, as shown in Fig 3. RQW is QSD-n doped. When current flows through p-n-n$^+$ junction, electrons and holes recombine inside the RQW. Photon with energy $\hbar\omega_0$, is emitted. Since RQW could be made as thick as 200 nm, it becomes possible to tune its width using charge depletion (depletion region width is typically more than 100 nm). Voltage V_t is applied to p-n junction. It modifiers internal potential and charge distribution in the proximity of RQW left boundary. Effective L_x of RQW changes and consequently G alters. G becomes V_t dependent and positions of energy levels (both in CB and VB) move on energy scale. Emitted photon energy $\hbar\omega_0$ is tuned. QSD doping of working area allows low resistive loses and high efficiency. Width of RQW can be maximized by choosing high G. At the same time QSD doping of working area can be regulated by adjusting n_{CON}.

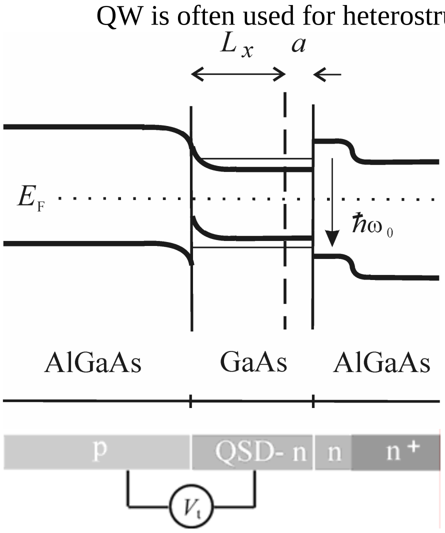

Fig.3 Energy diagram of tunable RQW laser.

Ballistic MOSFET transistors are widely discussed in the literature [7]. Using RQW in the source-drain channel will reduce quantum state density and consequently reduce scattering rates for both electrons and holes approximately G times. It makes ballistic transport much more pronounced. One of the possible designs of quantum state depression MOS (MOSQSD) transistor is shown in Fig. 4a (source and drain electrodes are omitted for simplicity). Channel made from undoped semiconductor has a single ridge. Insulator layer and gate electrode are grown on the top of the ridge like in conventional MOS transistor. QSD doping converts undoped semiconductor channel to n-type under the ridge. Far from the ridge value of E_F remains unaffected, as there is no QSD influence. We assume that the Fermi level in Y direction is flat, in absence of a source-drain and gate voltages. Then, energy diagram has the shape shown on Fig. 4b. There is a pocket for electrons in CB and a potential barrier for holes in VB. ΔE_F depends on G and consequently on dimensions a, L_x. Further, ridge height a can be changed by applying external voltage to the gate electrode and depleting charge under the insulator (like in conventional MOS transistor). Changing a, we alter geometry factor G and consequently ΔE_F, which in its turn modulates hole current in source-drain channel. Described design corresponds to p type source and drain electrodes or p-i-p transistor, since holes are charge carriers (barrier is in VB).

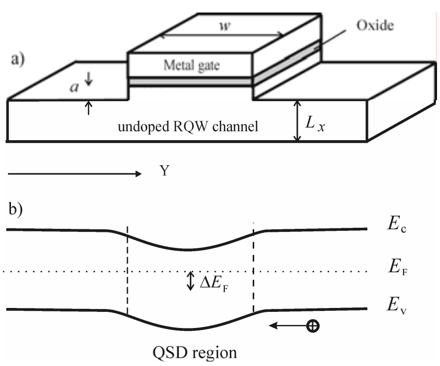

Fig. 4 a) p-i-p type QSD transistor
b) corresponding energy diagram.

If carriers are electrons, energy barrier in CB is required and consequently, different geometry should be used. In that case, gate electrode is in the valley and source and drain electrodes are on the ridges. Here QSD takes place in the regions of source and drain electrodes and turns undoped channel to n type. Conventional n-i-n type MOSFET has better ballistic properties than p-i-p type, as electrons have greater mean free path than holes. QSD increase mean free path of both electrons and holes *G* times (G=5 $\div$ 10) and p-i-p type ballistic MOSQSD transistor also becomes technologically feasible.

Main advantage of MOSQSD transistor over MOSFET is its improved ballistic properties. High value of *G* is needed to maximize mean free path of carriers. Another advantage is that QSD mechanism of channel current modulation works in parallel with conventional mechanism of modulation in MOSFET. QSD increases potential barrier for the given gate voltage. Our preliminary calculations show that MOSQSDT has higher voltage gain than MOSFET. Increase of voltage gain depends on *G* and is maximal for *G* somewhat exceeding unity. It follows that there is tradeoff between improving ballistic properties (needs G>>1) and improving voltage gain $(\text{needs } G \approx 1)$. One more advantage of p-i-p type shown in Fig.4 is that source-drain current do not flows in close proximity with the semiconductor insulator interface. Junction is in the “bay” under the gate electrode. This reduces the influence of insulator surface roughness and impurities on hole mobility.

QSD can be used in diffusion transport MOS transistors, bipolar transistors and diodes. Combination of QSD doping with conventional and modulation doping will enable number of new designs. QSD can also be used in other QW based devices, such as QW lasers and solar cells.

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