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Tunnel injection emitter structures with barriers comprising nanobridges

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Nanobridges which bypass the tunnel barrier in tunnel injection structures are investigated. The conditions leading to the formation of confined states within them are determined. It is shown that for tunnel barrier thicknesses in the 4–5 nm range confined hole states are likely to exist within the nanobridges. A new absorption feature, which has been observed only in structures comprising nanobridges, is assigned to transitions involving these hole states.

Absorption and emission properties of semiconductors are closely connected. Although nano-structurization offers additional degrees of freedom for tailoring optical properties, full decoupling of absorption and emission is not feasible. Total independence can be achieved, however, in systems of physically separated nanostructures being coupled only for energy transfer. There are various types of such nanostructures, among them the so-called *dot-in-a-well* design, consisting of quantum dots (QDs) being directly embedded into quantum wells (QWs) [1]. Very comparable to this design are *tunnel structures*, where QD and QW layers are separated by a several nm thick barrier, i.e. a barrier, where excitation transfer by tunneling becomes likely [2].

In this Letter, we address the carrier transfer in *tunnel injection structures* (TIS). TIS are tunnel structures with a special band alignment, where the QW ground state is located between QD ground and excited state; see Fig. 1a. In this way electrons, which are collected by the QW, can straight tunnel to the ground state of the QD and participate there, e.g., in radiative recombination. Thus the population of excited QD states can be diminished [3]. In regular QD structures, no matter if optically or electrically pumped, the population of excited states (hot carriers) always represents a major issue when proceeding to elevated excitation levels as required, e.g., for optoelectronic emitter applications. TIS have been prepared and a selective QD ground-state population was demonstrated [4]. Diode lasers based on TIS have been fabricated and successfully tested [3, 5].

Obviously, the key functionality of TIS, namely the achievement of a selective QD ground-state population, depends crucially on the design of the barrier between QW and QDs, which controls the excitation transfer between the QW collector and QD emitter. There have been several studies of the influence of the barrier (potential, thickness) on the kinetics in tunnel structures [2, 6, 7]. In TIS of the type addressed in this report, for barrier thicknesses $h > 5$ nm, good agreement was found with the Wentzel–Kramers–Brillouin (WKB) approximation. This approximation represents an analytical solution of the one-dimensional Schrödinger equation. For $h < 5$ nm, however, the experimentally observed carrier transfer took place faster than expected [4]. Potential reasons for the deviation from WKB could be the following: On the one hand, it can occur due to the combination of nano-objects with different dimensionality, 2D (QW) and 0D (QD). Alternatively, it can be assumed that the barriers undergo qualitative

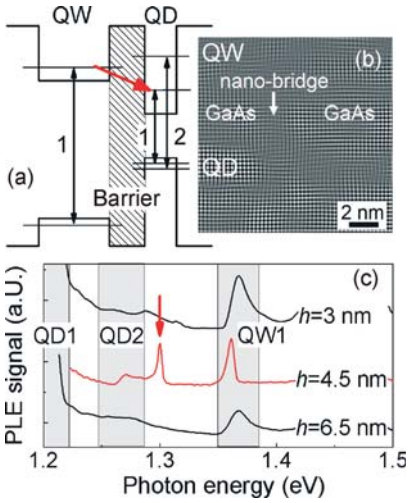

Figure 1 (online colour at: www.pss-rapid.com) (a) Band structure diagram of a TIS. The red arrow points to the carrier transfer mechanism that selectively populates the QD ground state. (b) High resolution transmission electron micrograph of the layer sequence of a TIS including a nanobridge. (c) PLE spectra from TIS with three different h values. The arrow indicates a distinct spectral feature seen exclusively in samples with $h = 4.5$ nm. The shaded regions indicate the known spectral positions of the QD- and QW-related transitions. The PLE monitor is set to 1.22 eV (QD1 ground-state transition).

structural changes towards small h. Indeed, transmission electron microscopy revealed structural modifications, namely the formation of distinct connections between the QWs and QDs, which have been named *nanobridges*; see micrograph of a InAs/GaAs-based TIS in Fig. 1b. Nanobridges were found to become intentionally producible by a trick in epitaxial growth: The standard growth sequence was turned and begins with the QD layer instead of the QW, followed by the barrier, and finalizes with the QW. Nanobridges were found to be almost cylindrically shaped with an In mole fraction (x) in the $0.15 < x < 0.6$ range. They appear for $h < 5$ nm and their diameter is $D \sim 2$ nm. We assume the formation of nanobridges to be driven by elastic stress on top of the QDs. This initiates diffusion of atoms, which leads to the formation of In-rich channels. In the case of thicker GaAs barriers, these channels are not expected to reach the QW layer.

Samples that contain nanobridges are expected to show a modification of the energy band structure, which gets translated into modified optical properties. Figure 1c shows photoluminescence excitation (PLE) spectra from three different TIS, which are based on a QW/barrier/QD structure being composed of $In_{0.15}Ga_{0.85}As/GaAs/In_{0.6}Ga_{0.4}As$, respectively. While nanobridges have been identified by TEM in both structures with $h = 4.5$ nm and 3 nm, only for the one with $h = 4.5$ nm an additional distinct PLE line at 1.3 eV has been observed; see arrow in Fig. 1c. This resonance is energetically located between the QD excited state (QD2) and the QW ground state (QW1). Clearly these findings indicate the presence of additional electronic states in these samples. On the other hand, it is not clear whether these states are directly related to nanobridges or not. Furthermore is remains open, why other samples, which definitely possess nanobridges (such as the sample with $h = 3$ nm in Fig. 1c), do not exhibit the PLE signature.

This experimental finding led us to considerations about the conditions for the existence of confined states within nanobridges. We begin with a single nanobridge being approximated by a cylinder with a diameter D and a height h being embedded into GaAs; see inset in Fig. 2. We neglect strain and assume a homogeneous mole fraction, which is given as a parameter in Figs. 2 and 3. Calculations of the electronic structure of such kinds of nanostructures have already been performed before, when treating cylindrical QDs by using the effective mass approximation [8–11]. Zegrya et al. [8] calculated the number of confined states in dependence of D within an InAs cylinder (in a GaAs matrix). In their example confined electronic states were found to require $D > 7.7$ nm for $h = 3$ nm. Following the approach of Lopez-Bolanos et al. [9] the D values fall slightly shorter, however, all tendencies including the dependence on D of confined electron states remain the same.

Figure 2 shows the results of our calculations, which are essentially based on the formalism used by Lopez-Bolanos et al. [9]. Within the frame of effective mass approximation it relies on separation of the problem for the cylinder with a diameter D and a height h into solutions for an infinite disk with diameter D and a rectangular potential well (2D layer) with thickness h. The first solution provides energy levels corresponding to the motion of elec-

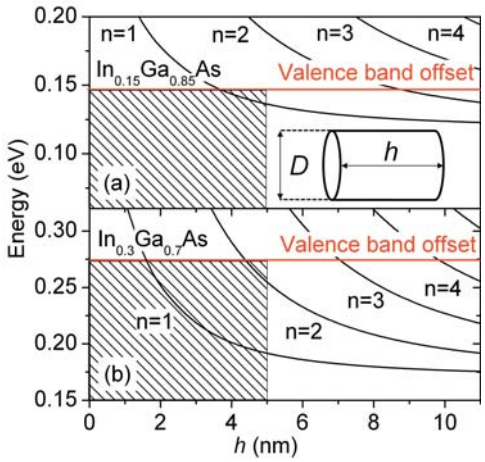

Figure 2 (online colour at: www.pss-rapid.com) Allowed hole energies within nanobridges vs. height h ($D = 2$ nm) for $In_{0.15}Ga_{0.85}As$ (a) and $In_{0.3}Ga_{0.7}As$ (b). The inset depicts the geometry of the nanobridge approximated by a cylinder, while the shaded areas point to the range where nanobridges get reproducibly created during epitaxial growth.

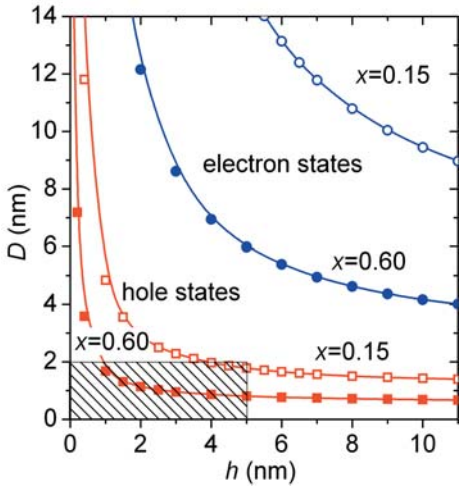

Figure 3 (online colour at: www.pss-rapid.com) Critical parameter combinations of diameter D and height h for the existence of at least one confined level within the nanobridge. The lines separate regions where confined states exist (top, right) from the region without confined states (bottom, left). The shaded area indicates the parameter range where nanobridges indeed have been observed.

trons transverse to the main axis of the cylinder, the second one for the motion along the main axis of the cylinder. The sum of both solutions provides the energy in the cylindrically shaped nanobridge with diameter D and height h. The parameters are the effective masses of electron and hole in $In_{0.15}Ga_{0.85}As$ nanobridges ($0.057m_0$ and $0.495m_0$) and in $In_{0.3}Ga_{0.7}As$ nanobridges ($0.050m_0$ and $0.480m_0$), respectively. The GaAs barrier values are $0.063m_0$ and $0.51m_0$. The conduction band offsets are 0.081 eV and 0.154 eV, the valence band offsets 0.144 eV and 0.274 eV for $x = 0.15$ and $x = 0.3$, respectively [12, 13].

Figure 2 shows the result for a given geometry of two particular nanobridges with different x. Assuming the nanobridge to consist of $In_{0.15}Ga_{0.85}As$, confined hole states exist for $h > 3.7–5$ nm, and in $In_{0.3}Ga_{0.7}As$ for $h > 1.7$ nm. Notice, for $h > 5$ nm, epitaxial growth does not produce nanobridges anymore. Thus there are only small h-intervals, where nanobridges comprising confined hole states do exist. For $In_{0.3}Ga_{0.7}As$, even a small existence range for an excited hole state is predicted. Assuming $D = 2$ nm as 'true' value, we conclude from Fig. 2 and the experimental findings given in Fig. 1, the nanobridge mole fraction to be between 0.15 and 0.3, probably closer to 0.15. Now we come to the impact of the outer shape of nanobridges to their energetic structure. Figure 3 summarizes the results of our calculations: Curves are plotted which give the parameter combination of D and h, which allows the presence of the ground states of electrons and holes for different x. The shaded area gives parameter combinations of D and h, where nanobridges indeed have been observed [4]. Thus it becomes clear, that confined hole states are likely to appear in practical nanobridges.

Therefore, the distinct line observed in the PLE spectrum of the sample with $h = 4.5$ nm, see Fig. 1c, is likely to be caused by an absorption process with the initial hole state being spread across a common valence band of QW, QD, and nanobridge, and the final state being the QD electron ground state. The absence of this line for the two other samples becomes clear as well: For the sample with $h = 6.5$ nm, there are no nanobridges, while the nanobridges in the sample with $h = 3$ nm are too small to have any confined states. This tentative assignment will be proved by future work with special emphasis on the carrier transfer between QW and QDs.

Summarizing, we analyzed the electronic band structure of nanobridges in tunnel barriers of TIS. We find the presence of confined hole states within these bridges to be likely. Such states are assumed to be responsible for the presence of additional absorption lines of TIS with nanobridges. We propose the intentional use of nanobridges for tailoring the carrier transfer in TIS.

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