Direct Creation of Quantum Well Excitons by Electron Resonant Tunneling

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(Received 15 December 1994; revised manuscript received 29 March 1995)

We have demonstrated a new tunneling process: the direct creation of GaAs quantum well excitons through electron resonant tunneling. The two-particle nature of such a tunneling process makes it different from the ordinary one-particle (electron, hole, or exciton) tunneling process in resonant tunneling conditions and results in different I-V characteristics. This resonant tunneling process may open a door toward electrically pumped excitonic cavity quantum electrodynamics and optoelectronic devices.

PACS numbers: 73.40.Gk, 71.35.+z, 78.55.Cr

The excitonic effect in resonant tunneling of photoexcited carriers is of great interest because of its fundamental quantum mechanical aspects and its potential application to tunneling devices [1]. The tunneling of free electrons (or holes) through a thin barrier between two adjacent quantum wells (QWs) has been shown to be a transfer from a direct (intrawell) exciton to an indirect (interwell) exciton [2]. Recently Lawrence *et al.* demonstrated that excitons can tunnel as a single entity between CdTe/CdMnTe and CdTe/CdZnTe asymmetric double QWs [3]. However, in those cases the excitons already existed before tunneling. The question we would like to address in this paper is: Can we *create* excitons in a QW directly by electron resonant tunneling? We will give the theoretical analysis and experimental evidence of the direct creation of GaAs QW excitons through an electron resonant tunneling process.

As shown in Fig. 1, our device consists of a p-doped $Al_{0.3}Ga_{0.7}As$ layer, a nondoped GaAs QW, a nondoped $Al_{0.3}Ga_{0.7}As$ barrier, and an n-doped GaAs layer. Without bias, the free holes in the p-doped $Al_{0.3}Ga_{0.7}As$ layer can thermally diffuse into the QW, while the free electrons in the n-GaAs layer are blocked by the intrinsic $Al_{0.3}Ga_{0.7}As$ barrier. As we apply a positive bias, the free electrons with an energy between the Fermi energy E_{Fn} and the conduction band edge E_{Cn} in the n-GaAs layer approach an exciton energy level inside the QW which is lower than the electron subband energy level by the exciton binding energy. Then the free electron can tunnel into the QW and combine with a hole to form an exciton directly. Such tunneling is resonantly enhanced when the energy of the initial state (the free electron in the n-GaAs and the subband hole in the QW) is equal to the energy of the final state (the exciton in the QW).

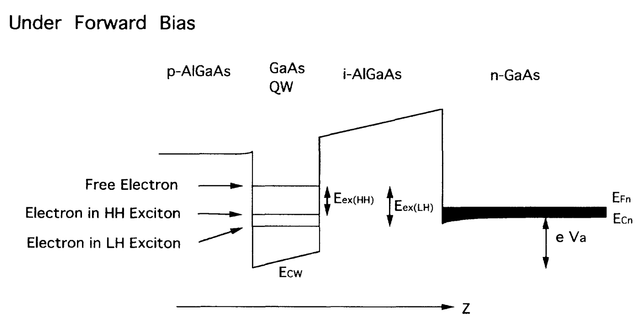

FIG. 1. The band structure of our tunneling device under forward bias.

Next we will derive the two-particle resonant tunneling condition. The initial state is the free electron in the n-GaAs layer with a wave vector parallel to the QW plane $\mathbf{k}_{e\parallel}$, and a wave vector perpendicular to the QW plane k_{ez}, and the subband hole inside the QW with a continuous transverse wave vector $\mathbf{k}_{h\parallel}$ and a quantized longitudinal momentum k_{hz} or energy E_{hz}. The final state is the 2D exciton, which is characterized by the transverse momentum $\mathbf{k}_{\mathrm{ex}\parallel}$ in terms of its center of mass, and the internal exciton binding energy E_{ex}, and the longitudinal energy given by the subband energy levels of electron E_{ez} and hole E_{hz}. Since the potential barrier is translationally invariant along the transverse direction, the transverse momentum is conserved, i.e.,

$$\mathbf{k}_{e\parallel} + \mathbf{k}_{h\parallel} = \mathbf{k}_{\mathrm{ex}\parallel} . \qquad (1)$$

However, the transverse kinetic energy is not necessarily conserved, i.e.,

$$\frac{\hbar^2 k_{e\parallel}^2}{2m_e} + \frac{\hbar^2 k_{h\parallel}^2}{2m_{h\parallel}} - \frac{\hbar^2 k_{\mathrm{ex}\parallel}^2}{2M} = \frac{\hbar^2 k_r^2}{2\mu} \neq 0 , \qquad (2)$$

where $m_{h\parallel}$ is the transverse effective mass of the subband hole, $M = m_e + m_{h\parallel}$ is the total mass of the 2D exciton, $\mu^{-1} = m_e^{-1} + m_{h\parallel}^{-1}$ is its internal reduced mass, and k_r is determined by the relative velocity of the initial electron and hole,

$$\frac{\mathbf{k}_r}{\mu} = \frac{\mathbf{k}_{e\parallel}}{m_e} - \frac{\mathbf{k}_{h\parallel}}{m_{h\parallel}} . \qquad (3)$$

However, the total energy must be conserved, i.e.,

$$\left(\frac{\hbar^2 k_{e\parallel}^2}{2m_e} + \frac{\hbar^2 k_{ez}^2}{2m_e}\right)\left(\frac{\hbar^2 k_{h\parallel}^2}{2m_{h\parallel}} + E_{hz}\right) + eV_a = \frac{\hbar^2 k_{\mathrm{ex}\parallel}^2}{2M} + E_{\mathrm{ex}} + E_{ez} + E_{hz} , \qquad (4)$$

where $V_a = V - V_b$, V is the applied forward bias, and V_b is the built-in voltage of the pn junction.

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Since the energy difference between the hole subbands inside the QW is much larger than the kinetic energy of holes and electrons, we neglect the probability of hole transition from one subband to another. From the total energy and transverse momentum conservation, we get the resonant tunneling condition

$$\frac{\hbar^2 k_{ez}^2}{2m_e} + \frac{\hbar^2 k_r^2}{2\mu} = E_{\mathrm{ex}} + E_{ez} - eV_a . \qquad (5)$$

In our case, E_{ex} is on the order of 10 meV, $\hbar^2 k_{ez}^2/2m_e$ and $\hbar^2 k_r^2/2\mu$ are on the order of 1 meV, respectively.

This resonant tunneling condition is different from the ordinary resonant tunneling condition of an electron into the electron subband inside the QW. In that case the transverse momentum conservation and total energy conservation give

$$\frac{\hbar^2 k_{ez}^2}{2m_e} = E_{ez} - eV_a . \qquad (6)$$

This condition implies that all electrons with certain k_{ez} can resonantly tunnel in no matter what initial transverse momentum $k_{e\parallel}$ they have. Since the resonant tunneling into an exciton level is a two-particle problem, the required k_{ez} for an electron to tunnel in depends on which hole state the electron will combine to form an exciton. In other words, $k_{e\parallel}$ and $k_{h\parallel}$ determine the required k_{ez}. Therefore different initial electron states could tunnel into the same final exciton state but with different initial hole states. This broadens the resonant tunneling peak in a current-voltage (I-V) curve. For instance, at low bias where $\hbar^2 k_{ez}^2/2m_e < E_{\mathrm{ex}} + E_{ez} - eV_a$, resonant electron tunneling into the exciton state is still possible since an electron can tunnel to combine with a hole moving laterally in the opposite direction so that the electron-hole excess transverse kinetic energy $\hbar^2 k_r^2/2\mu$ will add up with $\hbar^2 k_{ez}^2/2m_e$ to reach $E_{\mathrm{ex}} + E_{ez} - eV_a$.

After the excitons are created inside the QW, they either relax to $k_{\mathrm{ex}\parallel} = 0$ by phonon scattering and then radiatively decay, or dissolve into the free electron and the subband hole by the electron tunneling back from the QW to the n-GaAs layer. By the WKB method we have estimated the typical exciton lifetime set by the second process, and found that it is at least 5 times longer than the typical exciton relaxation and radiative recombination lifetime. Therefore the exciton relaxation and radiative recombination is dominant, and the net tunneling current is hence approximately given by the forward tunnel current.

We can treat the tunneling process as a transition from an initial state to a final state [4], and calculate the tunneling probability P by Fermi's golden rule, i.e.,

$$P = (2\pi/\hbar)\,|\langle f|H_t|i\rangle|^2 \delta(E_i - E_f) , \qquad (7)$$

where H_t is the tunneling Hamiltonian which describes the effects of the potential barrier and the Coulomb interaction between the electron and hole, $|i\rangle = |\mathbf{k}_{e\parallel}, k_{ez}\rangle\,|\mathbf{k}_{h\parallel}, E_{hz}\rangle$ is the initial state (free electron and subband hole), and $|f\rangle = |\mathbf{k}_{\mathrm{ex}\parallel}, E_{\mathrm{ex}}; E_{ez}, E_{hz}\rangle$ is the final state.

To get the total tunneling current density J_T, we integrate the tunneling probability over all possible combinations of initial and final states, taking into account the Fermi-Dirac distribution of electrons $f_e(\mathbf{k}_{e\parallel}, k_{ez})$ and holes $f_h(\mathbf{k}_{h\parallel}, E_{hz})$ in the initial states, i.e.,

$$J_T = \int P f_e(\mathbf{k}_{e\parallel}, k_{ez}) f_h(\mathbf{k}_{h\parallel}, E_{hz}) \frac{1}{(2\pi)^2}\, d\mathbf{k}_{\mathrm{ex}\parallel} \times \frac{1}{(2\pi)^2}\, d\mathbf{k}_{e\parallel} \frac{1}{(2\pi)^2}\, d\mathbf{k}_{h\parallel} \frac{1}{(2\pi)}\, dk_{ez} . \qquad (8)$$

Since in our device the exciton density n_{ex} inside the QW is much smaller than the Mott transition density, i.e., $n_{\mathrm{ex}} \ll 1/\pi a_B^2$ (a_B is the exciton Bohr radius), J_T is effectively independent of the population of the final states (excitons), but is dependent on the density of holes inside the QW and the density of electrons in the n-GaAs layer. A higher hole density inside the QW will give a larger tunneling current J_T. However, if the hole density is too high, the screening effect of hole gas will prevent the formation of excitons by exciton–free-carrier scattering. We estimated that the 2D hole density inside the QW should be larger than $1 \times 10^9\ \mathrm{cm}^{-2}$ to observe J_T above the background thermionic emission current at 4 K, and it should be less than $1 \times 10^{11}\ \mathrm{cm}^{-2}$ to avoid the screening effect. In our samples, the hole density inside the QW is determined by the acceptor concentration in the p-$Al_{0.3}Ga_{0.7}As$ layer and the space charge field created between the p-$Al_{0.3}Ga_{0.7}As$ layer and the nondoped QW, and it is estimated to be on the order of $1 \times 10^{10}\ \mathrm{cm}^{-2}$ [5].

Figure 2 shows the calculated tunneling current density J_T as a function of the effective bias V_a in the regime close to the resonant tunneling bias into the first electron subband of a 50 Å QW. The $Al_{0.3}Ga_{0.7}As$ barrier is

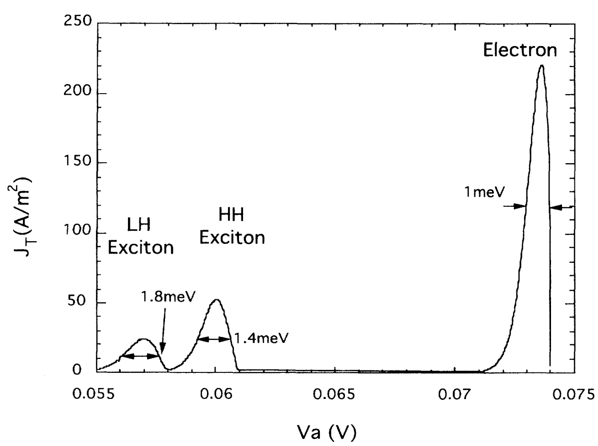

FIG. 2. Numerically calculated tunneling current density J_T as a function of bias V_a.

100 Å thick. The hole density inside the QW is 1×10^{10} cm^{-2}. The Fermi level in the n-GaAs layer E_{Fn} is 1 meV above the conduction band edge E_{Cn}. The 1s light-hole (LH) exciton binding energy is about 16 meV, and 1s heavy-hole (HH) exciton binding energy is about 12 meV [6]. The first current peak corresponds to the resonant tunneling into the 1s LH exciton state below the first electron subband. The second peak corresponds to the tunneling into the 1s HH exciton state. The third peak represents the normal resonant tunneling of electrons into the first electron subband in the QW. In this calculation, we neglect the inhomogeneous broadening of QW energy levels. Therefore the width of the tunneling peaks is determined by the energy spread of initial electrons and holes. We can see that the first and second peaks are slightly broader than the third peak, which agrees with our qualitative prediction from the resonant tunneling condition.

In this paper we present experimental results of two samples grown by molecular beam epitaxy (MBE) on $n^+ \langle 100 \rangle$ GaAs substrates. In the first sample, the GaAs QW is 100 Å wide, and the $Al_{0.3}Ga_{0.7}As$ barrier is 75 Å wide. The p-$Al_{0.3}Ga_{0.7}As$ layer is doped at 1×10^{18} cm^{-3}, and the n-GaAs layer is doped at 4×10^{16} cm^{-3}. The lateral size of the mesa is 100×100 μm. The sample was cooled down to 4.2 K, and its I-V characteristic was measured by a HP 4155A semiconductor parameter analyzer under constant voltage operation mode.

The inset of Fig. 3 shows the equivalent measurement circuit. The measured current I_s is the sum of the tunneling current I_d and the leakage current I_c. The leakage current I_c is due to surface recombination, thermionic emission of electrons into the QW, thermionic emission, and tunneling of holes from the QW to the n-GaAs layer. The measured voltage $V_s = V_d + I_s R_s$, where V_d is the voltage drop across the tunnel junction, and R_s is the resistance in series with the tunnel junction, including the resistance of the Ohmic contact, the bulk layers, and the substrate.

As shown in Fig. 3, the measured I_s-V_s curve of our first sample shows clearly two resonant tunneling peaks very close to each other. The series resistance R_s was measured to be about 3 Ω. By subtracting the voltage drop $I_s R_s$ over the series resistance from the measured V_s, we found the actual junction voltage (V_d) separation between these two peaks is about 14 meV. According to the theoretical calculation [6] and photoluminescence excitation (PLE) experiments [7–9], the LH-exciton binding energy in a 100 Å wide $GaAs/Al_{0.3}Ga_{0.7}As$ QW is about 13 meV, and HH-exciton binding energy is about 10 meV. Therefore we believe that the first current peak corresponds to the resonant tunneling into the exciton levels below the first electron subband in the QW, and the second current peak corresponds to the resonant tunneling into the first electron subband level of the QW. From the PL experiment at 4.2 K, we found that the QW exciton line width was about 6 meV. This indicates that in this sample the QW energy level broadening due to the QW width fluctuation and impurities is rather large. That is why the tunneling peaks are too broad to separate the tunneling peak into the LH-exciton level from that into the HH-exciton level. The measured exciton tunneling peak

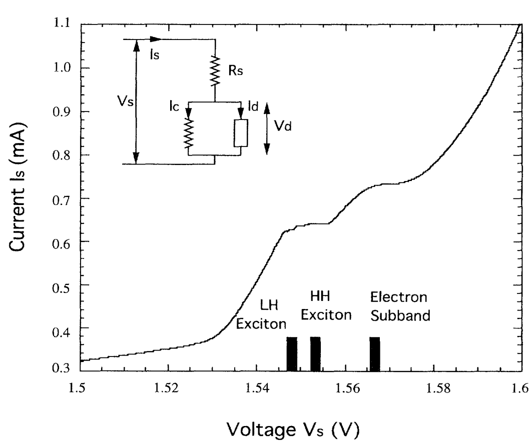

FIG. 3. The measured current I_s as a function of the voltage V_s for the first sample. The inset is the equivalent circuit of the I-V measurement.

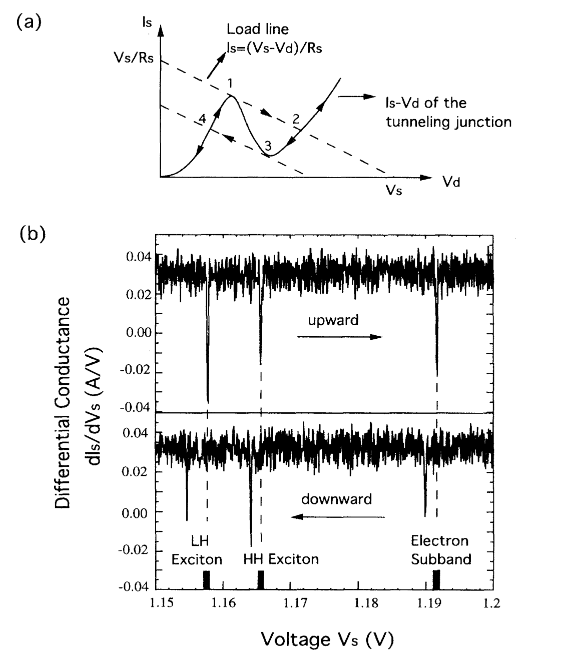

FIG. 4. (a) A resonant tunneling peak in I_s-V_d results in a hysteresis loop in I_s-V_s when the load resistance R_s is larger than the absolute value of the negative differential resistance of the tunnel junction. (b) The measured differential conductance dI_s/dV_s as a function of the voltage V_s for the second sample when V_s is swept upward and downward.

has a larger amplitude than the calculation. This discrepancy is due to the inaccuracy in the estimation of the hole density in the QW.

In order to reduce the width of the tunneling peaks, we grew a second sample with a narrower QW (50 Å) to increase the separation between the QW energy levels. We also introduced growth interruption at the QW interfaces to reduce the QW width fluctuation. To further narrow each tunneling peak, we decreased the doping of the n-GaAs layer to 8×10^{15} cm^{-3}. The barrier width is 110 Å. Unfortunately in this sample the series resistance R_s is increased to $15\,\Omega$ due to the low doping of the n-GaAs layer. Since the series resistance R_s is now larger than the absolute value of the negative differential resistance of the tunnel junction, a resonant tunneling peak in the I_s-V_d characteristic of the tunnel junction corresponds to a hysteresis loop in the measured I_s-V_s curve [Fig. 4(a)]. This is because the measured I_s corresponds to the intersection point of the load line $I_s = (V_s - V_d)/R_s$ and the I_s-V_d curve. As V_s increase, I_s will increase until it reaches the resonant tunneling peak (point 1). Then I_s will jump downward from point 1 to point 2. When V_s decreases, I_s will decrease until it reaches the valley (point 3), and then it will jump upward from point 3 to point 4.

Figure 4(b) shows the measured differential conductance dI_s/dV_s as a function of the voltage V_s when V_s is swept upward and downward. The three jumps in dI_s/dV_s as V_s is swept upward and the three slightly downshifted jumps in dI_s/dV_s as V_s is swept downward correspond to three hysteresis loops, which indicates the existence of three resonant tunneling peaks. After subtracting I_sR_s from V_s, we found the actual junction voltages V_d corresponding to the three resonant tunneling peaks were 1.095, 1.099, and 1.112 V. The separation in V_d between the first and third tunneling peaks is 17 mV, which is close to the 1s LH-exciton binding energy (~16 meV) in the 50 Å QW of our second sample [6,7]. The separation between the second and third tunneling peaks is 13 mV, which is also close to the 1s HH-exciton binding energy (~12 meV) [6,7]. Therefore it suggests that the three tunneling peaks we have observed correspond to the resonant tunneling into the LH-exciton level, the HH-exciton level, and the first electron subband level in the QW. From the voltages at which the measured current I_s jumps up and down in each hysteresis loop, we estimate the widths of the LH exciton, HH exciton, and electron subband resonant tunneling peaks are about 2.8, 1.5, and 1.5 mV, respectively, which are close to the theoretically calculated widths 1.8, 1.4, and 1.0 mV of these three resonant tunneling peaks. However, the leakage current I_c of our second sample is very large, and thus the tunneling current is too small to get the exact peak value.

In conclusion, we have shown theoretically and demonstrated experimentally a new resonant tunneling process: the direct creation of QW excitons through electron resonant tunneling. Since such a process involves two particles (an electron and a hole), the resonant tunneling condition and associated I-V characteristics are different from those of an ordinary one-particle (electron, hole, or exciton) tunneling process. In addition to its own interest as a new physical process, the direct creation of QW excitons by resonant electron tunneling can be utilized to make an electrical current driven excitonic optoelectronic device and excitonic cavity quantum electrodynamics [10].

We would like to thank Professor W. Harrison for stimulating discussions, and Dr. L. Eng and G. Li for their advice and help with the MBE growth.

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