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Theory of direct creation of quantum-well excitons by hole-assisted electron resonant tunneling

H. Cao, G. Klimovitch, G. Björk, and Y. Yamamoto*
ERATO Quantum Fluctuation Project, E. L. Ginzton Laboratory, Stanford University, Stanford, California 94305
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We have investigated a resonant tunneling process: the direct creation of GaAs quantum well excitons through hole-assisted electron resonant tunneling. The current density of this tunneling process is on the same order of magnitude as the usual electron resonant tunneling current density. However, the two-particle nature of such a tunneling process makes it different from the conventional one-particle (electron, hole, or exciton) tunneling process, and in fact it is another type of assisted tunneling as compared with the phonon-assisted tunneling. This tunneling process may open a door toward electrically pumped excitonic cavity quantum electrodynamics and optoelectronic devices.

I. INTRODUCTION

Control of spontaneous emission by a microcavity has been a great success in the reduction of threshold of semiconductor lasers.[1–3] However, the spontaneous emission coupling efficiency in a planar semiconductor microcavity is limited by the lateral leakage of spontaneous emission from the isotropical radiators, e.g., an electron-hole pair dipole. Recently the interest in spatially coherent quantum-well (QW) excitons with a transverse (in the QW plane) momentum $\mathbf{k}_{\mathrm{ex}\|} \sim 0$ has surged, because such excitons cannot only induce a rapid superradiative decay, but can also preferably radiate in the normal direction of the QW, leading to a better coupling with the resonant vertical mode of a planar cavity.[4] However, until now an efficient creation of $\mathbf{k}_{\mathrm{ex}\|} \sim 0$ excitons has only been achieved by resonant optical pumping. For applications in optoelectronics, efficient creation of $\mathbf{k}_{\mathrm{ex}\|} \sim 0$ excitons by electrical pumping is required.

On the other hand, the excitonic effect in resonant tunneling of photoexcited carriers is also of great interest because of its fundamental quantum mechanical aspects and its potential application to tunneling devices.[5] The tunneling of free electrons (or holes) through a thin barrier between two adjacent QW's has been shown to be a transfer from a direct (intrawell) exciton to an indirect (interwell) exciton.[6] Recently Lawrence *et al.* demonstrated that excitons can tunnel as a single entity between $\mathrm{CdTe/Cd_{1-x}Mn_xTe}$ and $\mathrm{CdTe/Cd_{1-x}Zn_xTe}$ asymmetric double QW's.[7] However, in those cases the excitons already existed before tunneling.

Recently, we have demonstrated experimentally a way of direct creation of excitons in a GaAs QW, i.e., by electron resonant tunneling.[8] In this paper, we will present a detailed theoretical analysis of this tunneling process. The advantage of this tunneling process is that under certain bias conditions most excitons created in this way initially have $\mathbf{k}_{\mathrm{ex}\|} \sim 0$.

The outline of this paper is as follows. In Sec. II, we will present a qualitative analysis of this tunneling process, illustrate its hole-assisted electron resonant tunneling nature, and compare it with the conventional electron resonant tunneling process. In Sec. III, we will briefly review the calculation of conventional electron resonant tunneling current density. In Sec. IV, we will calculate the current density of this hole-assisted electron resonant tunneling process, and the initial transverse momentum $\mathbf{k}_{\mathrm{ex}\|}$ distribution of excitons created by this tunneling process. In Sec. V, we will give a brief summary.

II. QUALITATIVE ANALYSIS

As shown in Fig. 1, our device consists of a p-type doped $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ layer, a nondoped GaAs QW, a nondoped $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ barrier, and a n-type doped GaAs

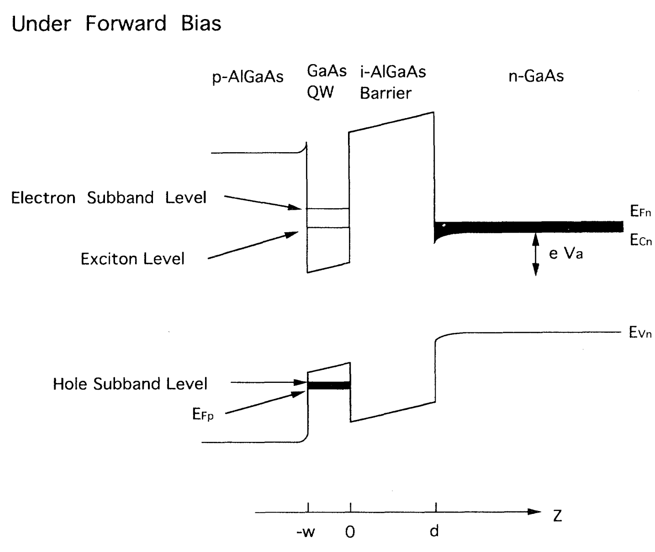

FIG. 1. The band structure of our tunneling device under forward bias.

layer. Without bias, the free holes in the p-type doped $Al_xGa_{1-x}As$ layer can thermally diffuse into the QW, while the free electrons in the n-type GaAs layer are blocked by the intrinsic $Al_xGa_{1-x}As$ 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-type GaAs layer approach an exciton energy level inside the QW, which is lower than the electron subband energy level by the exciton binding energy E_{ex}. 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 (a free electron in the n-type GaAs layer and a subband hole in the QW) is equal to the energy of the final state (an exciton in the QW).

Let us derive this two-particle resonant tunneling condition. The initial state is the free electron in the n-type GaAs layer with a wave vector parallel to the QW plane $\mathbf{k}_{e\|}$, and a wave vector perpendicular to the QW plane $\mathbf{k}_{ez}$, and the subband hole inside the QW with a continuous transverse wave vector $\mathbf{k}_{h\|}$ and a quantized longitudinal energy E_{hz}. The final state is the two-dimensional (2D) exciton, which is characterized by the transverse momentum $\mathbf{k}_{\text{ex}\|}$ in terms of its center of mass, 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 quantum-well plane, the transverse momentum is conserved, i.e.,

$$\mathbf{k}_{e\|} + \mathbf{k}_{h\|} = \mathbf{k}_{\text{ex}\|} \ . \tag{1}$$

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

$$\frac{\hbar^2 k_{e\|}^2}{2m_e} + \frac{\hbar^2 k_{h\|}^2}{2m_{h\|}} - \frac{\hbar^2 k_{\text{ex}\|}^2}{2M} = \frac{\hbar^2 k_r^2}{2\mu} \neq 0 \ , \tag{2}$$

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

$$\frac{\mathbf{k}_r}{\mu} = \frac{\mathbf{k}_{e\|}}{m_e} - \frac{\mathbf{k}_{h\|}}{m_{h\|}} \ . \tag{3}$$

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

$$\left(\frac{\hbar^2 k_{e\|}^2}{2m_e} + \frac{\hbar^2 k_{ez}^2}{2m_e}\right) + \left(\frac{\hbar^2 k_{h\|}^2}{2m_{h\|}} + E_{hz}\right) + eV_a = \frac{\hbar^2 k_{\text{ex}\|}^2}{2M} + E_{ez} - E_{\text{ex}} + E_{hz} \ , \tag{4}$$

where $V_a = V - V_b$, V is the applied forward bias, and V_b is the builtin voltage of the p-i-n junction.

Since the energy difference between the hole (electron) subbands inside the QW is much larger than the kinetic energy of holes (electrons) in an exciton, 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

$$\frac{\hbar^2 k_{ez}^2}{2m_e} = E_{ez} - E_{\text{ex}} - eV_a - \frac{\hbar^2 k_r^2}{2\mu} \ . \tag{5}$$

This 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

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

This condition implies that all electrons with certain k_{ez} can resonantly tunnel in no matter what initial transverse momentum $\mathbf{k}_{e\|}$ 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 with to form an exciton. In other words, $\mathbf{k}_{e\|}$ and $\mathbf{k}_{h\|}$ 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 results in broader resonant tunneling peak in a current-voltage (I-V) curve (in comparison with the peak from electron tunneling into an electronic subband).

As an example, let us consider the upper limit $V_{\max}$ and lower limit $V_{\min}$ of the effective bias V_a at $T = 0$ K. For electron resonant tunneling into an electron level in the QW,

$$V_{\max} = E_{ez}/e, \ V_{\min} = (E_{ez} - E_{Fe})/e.$$

For electron resonant tunneling into an exciton level in the QW,

$$V_{\max} = (E_{ez} - E_{ex})/e \ ,$$

$$V_{\min} = \begin{cases} (E_{ez} - E_{\text{ex}} - E_{Fe} - |E_{Fh}|)/e & \text{if } k_{Fe} > k_{Fh} \\ [E_{ez} - E_{\text{ex}} - E_{Fe} + E_{Fh} + \hbar^2(k_{Fh} - k_{Fe})^2/2M]/e & \text{if } k_{Fe} < k_{Fh} \ , \end{cases} \tag{7}$$

where E_{Fe} is the electron's Fermi energy with respect to the conduction band edge in the n-type GaAs layer, E_{Fh} is the hole's Fermi energy with respect to the valence band edge inside the QW, and k_{Fe} (k_{Fh}) is the Fermi $\mathbf{k}$ vector of electron (hole), i.e., $k_{Fe} = \sqrt{2m_e E_{Fe}}$ ($k_{Fh} = \sqrt{2m_{h\|}|E_{Fh}|}$). Below we only consider the case when $k_{Fe} > k_{Fh}$.

From the above equations, we can see that the variation range of the bias voltage for the resonant electron tunneling into the exciton level is $(E_{Fe} + |E_{Fh}|)/e$, while for the resonant tunneling process into the electron level the variation range of bias is only E_{Fe}/e. At low bias regime where $eV_a < E_{ez} - E_{\rm ex} - E_{Fe}$, even though $\hbar^2 k_{ez}^2/2m_e < E_{ez} - E_{\rm ex} - eV_a$ and thus the conventional electron resonant tunneling followed by a subsequent formation of an exciton is forbidden, electron resonant 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 $E_{\rm ex} + E_{ez} - eV_a$. In this sense, this process is a hole-assisted electron resonant tunneling, which creates excitons directly in the QW. It is another type of assisted tunneling with phonon assisted tunneling being the most prominent representative.[9,10]

On the other hand, excitons formed under such low bias have very small transverse momentum, i.e., $\mathbf{k}_{\rm ex\|} = \mathbf{k}_{e\|} + \mathbf{k}_{h\|} \simeq 0$. The range of $k_{\rm ex\|}$ under bias V_a is

$$0 \le k_{\rm ex\|} \le \frac{\sqrt{2M\,e(V_a - V_{\rm min})}}{\hbar} \,.$$

Therefore at minimum bias, i.e., $V_a = V_{\rm min}$, all excitons created have $k_{\rm ex\|} = 0$.

III. CONVENTIONAL ELECTRON RESONANT TUNNELING

Under a positive bias, when the energy of electron in the n-type GaAs layer approaches an electron subband inside the QW, an electron can resonantly tunnel through the barrier into the electron level of the QW. This tunneling process can be treated as a transition from an initial state $|i\rangle = |\mathbf{k}_{e\|}, k_{ez}\rangle$ to a final state $|f\rangle = |\mathbf{k}'_{e\|}, E_{ez}\rangle$.[11] According to Fermi's golden rule, the tunneling probability is

$$P_{i\to f} = \frac{2\pi}{\hbar}\,|M_e(k_{ez})|^2\,(2\pi)^2\,\delta(\mathbf{k}_{e\|} - \mathbf{k}'_{e\|}) \times\delta\left(\frac{\hbar^2 k_{ez}^2}{2m_e} - E_{ez} + eV_a\right)\,, \tag{8}$$

where M_e is the tunneling matrix element.

Since the Hamiltonian is time reversible, to get the matrix element, we consider the reverse process, namely, when one electron inside the QW tunnels out to the n-type GaAs layer. Assuming that all the electron states in the n-type GaAs layer are empty, from Eq. (8) the electron tunneling-out rate can be expressed as follows:

$$\frac{1}{\tau_e} = \frac{m_e}{\hbar^3\,k_{ez}}\,|M_e(k_{ez})|^2\,. \tag{9}$$

Using the WKB approximation, we have calculated the electron tunneling-out rate in our structure:

$$\frac{1}{\tau_e} \simeq \frac{4\hbar k_{ez}}{m_e w}\,\exp\left(-\frac{4d}{3eV_a}\sqrt{\frac{2m_e}{\hbar^2}}[(V_e - E_{ez} + eV_a)^{3/2} -(V_e - E_{ez})^{3/2}]\right)\,. \tag{10}$$

From Eqs. (9) and (10), the tunneling matrix element is

$$|M_e(k_{ez})|^2 \simeq \frac{8\hbar^2(E_{ez} - eV_a)}{m_e w} \times\exp\left(-\frac{4d}{3eV_a}\sqrt{\frac{2m_e}{\hbar^2}}[(V_e - E_{ez} + eV_a)^{3/2} -(V_e - E_{ez})^{3/2}]\right)\,. \tag{11}$$

After the electrons resonantly tunnel into the QW, they either recombine with holes or tunnel back to the n-type GaAs layer from the QW. From (10), we have estimated that the typical tunneling time constant for our structure is about 50 ps,[12] which is much longer than the typical electron-hole recombination time constant ($\sim$ 10 ps) due to the presence of the many holes inside the QW. Therefore, the electron population inside the QW is very small, and the tunneling-back current is negligible.

To get the electron resonant tunneling current density J_e, we integrate the tunneling rate over all the initial electron states in the n-type GaAs layer and the final electron states in the QW, taking into account the Fermi-Dirac distribution of electrons in the initial states,[13–15] and get

$$J_e = \frac{em_e^2|M_e|^2 k_B T}{2\pi\hbar^4\sqrt{2m_e(E_{ez} - eV_a)}} \times\ln\{1 + \exp\left[(E_{Fe} - E_{ez} + eV_a)/(k_B T)\right]\}\,. \tag{12}$$

Using (11), we can find the asymptotic behavior of J_e at the upper and lower limit of the bias V_a. When V_a approaches its upper limit $V_{\rm max} = E_{ez}/e$, the z-direction velocity $\hbar k_{ez}/m_e$ of electrons that satisfy the resonant tunneling condition is proportional to $(E_{ez} - eV_a)^{1/2}$, and thus goes to zero. Therefore J_e, which is proportional to k_{ez}, also approaches zero as $(V_{\rm max} - V_a)^{1/2}$. When V_a approaches its lower limit $V_{\rm min} = (E_{ez} - E_{Fe})/e$ at $T = 0$ K, the number of electrons, which can tunnel into the QW, goes to zero as a function of $V_a - V_{\rm min}$. Therefore J_e, which is proportional to the number of electrons that can tunnel, also approaches zero as $V_a - V_{\rm min}$.

IV. EXCITON FORMATION BY HOLE-ASSISTED ELECTRON RESONANT TUNNELING

In this case, the initial state is a free electron in the n-type GaAs layer and a subband hole in the QW, i.e., $|i\rangle = |\mathbf{k}_{e\|}, k_{ez}\rangle|\mathbf{k}_{h\|}, E_{hz}\rangle$, and the final state is a 2D exciton in the QW, i.e., $|f\rangle = |\mathbf{k}_{\rm ex\|}, E_{\rm ex}; E_{ez}, E_{hz}\rangle$. From Fermi's Golden rule, the tunneling probability is

$$P_{i\to f} = \frac{2\pi}{\hbar}\,|M_{\rm ex}(k_{ez})|^2\,(2\pi)^2\,\delta(\mathbf{k}_{e\parallel}+\mathbf{k}_{h\parallel}-\mathbf{k}_{{\rm ex}\parallel}) \times\delta\left(\frac{\hbar^2k_{ez}^2}{2m_e}+\frac{\hbar^2k_r^2}{2\mu}-E_{ez}+E_{\rm ex}+eV_a\right)\,, \quad (13)$$

where $M_{\rm ex}$ is the tunneling matrix element.

Again, in order to get the matrix element $M_{\rm ex}$, we consider the reverse process, i.e., an exciton in the QW dissolves into a free electron and a subband hole by the electron tunneling back from the QW to the n-type GaAs layer. Assuming that all the electron states in the n-type GaAs layer are empty, the tunneling-out rate can be expressed as follows:

$$\frac{1}{\tau_{\rm ex}} = \int\frac{2\pi}{\hbar}\,|M_{\rm ex}|^2\,\delta\biggl(\frac{\hbar^2k_{ez}^2}{2\mu}+\frac{\hbar^2k_r^2}{2\mu}+eV_a -E_{ez}+E_{\rm ex}\biggr)\,\frac{1}{2\pi}\,dk_{ez}\,\frac{1}{(2\pi)^2}\,d\mathbf{k}_r\,. \quad (14)$$

Since the tunneling rate is independent of the initial exciton's center of mass transverse motion, we assume $k_{{\rm ex}\parallel}=0$, or in other words, we move to the exciton's center of mass frame.

Next we will use WKB method to estimate the tunneling-out rate $1/\tau_{\rm ex}$. In a thin QW where the well width w is equal to or less than the exciton Bohr radius a_B, the 2D approximation for the exciton wave function inside the QW gives

$$\psi_i(\mathbf{r}_\parallel,z_e,z_h) = \left(\frac{8}{\pi a_B{}^2}\right)^{1/2} \times\exp(-2r_\parallel/a_B)\,\psi_e(z_e)\psi_h(z_h)\,, \quad (15)$$

where $\mathbf{r}_\parallel$ is the electron-hole relative coordinate in the plane parallel to the QW plane; $\psi_e(z_e)$ $[\psi_h(z_h)]$ is the confined electron (hole) wave function in the z direction. It should be pointed out that due to the high hole density in the QW, the screening effect will modify the simple hydrogenlike 2D exciton wave function, which has been neglected in our first-order calculation.

For a high and thin barrier, as the electron tunnels through the barrier to its right edge, the exciton wave function can be approximated as

$$\psi_i(\mathbf{r}_\parallel,z_e=d,z_h) = 2\left(\frac{8}{\pi a_B^2}\right)^{1/2}\exp(-2r_\parallel/a_B)\,\psi_e(z_e=0)\exp(-b/2)\,\psi_h(z_h)\,, \quad (16)$$

where $\kappa(z_e)=\sqrt{(2m_e/\hbar^2)(V_{\rm eff}-E_{ez}+eV_a)}$, and

$$b\equiv 2\int_0^d\kappa(z_e)dz_e = \frac{4d\sqrt{2m_e}}{3\hbar\,eV_a} \times[(V_{\rm eff}-E_{ez}+eV_a)^{3/2}-(V_{\rm eff}-E_{ez})^{3/2}], \quad (17)$$

where $V_{\rm eff}$ is the effective barrier height for the electron. Since the barrier height is increased by the exciton binding energy $E_{\rm ex}$ and decreased by the Coulomb interaction between the electron in the barrier and the hole in the QW, the upper and lower bound for $V_{\rm eff}$ is

$$V_e < V_{\rm eff} < V_e + E_{\rm ex}. \quad (18)$$

From this bound and Eq. (17), we get the range of b. For the typical parameters in our structure, i.e., $V_e\sim 230$ meV, $E_{\rm ex}\sim 10$ meV, and barrier width $d\sim 100$ Å, we find that $\Delta b/b < 0.3$. Therefore the error for $\exp(-b/2)$ is within 15% no matter whether we use the upper or the lower bound for $V_{\rm eff}$.

To match both the wave function and its derivative at $z_e=d$, we also consider the reflected component of the wave function inside the barrier, which is increasing with z_e $(0\le z_e\le d)$. It is the reflected wave that results in factor 2 in the right hand side of (16).

After the exciton has dissolved into a free electron in the n-type doped GaAs layer and a subband hole in the QW, the wave function becomes

$$\psi_f(\mathbf{r}_\parallel,z_e,z_h) = \exp(i\mathbf{k}_r\cdot\mathbf{r})\exp[ik_{ez}(z_e-d)]\psi_h(z)\,, \quad (19)$$

where $\mathbf{k}_r$ is the electron-hole relative transverse momentum.

We match the in-barrier wave function $\psi_i(\mathbf{r}_\parallel,z_e,z_h)$ with a linear combination of the outgoing wave function $\psi_f(\mathbf{r}_\parallel,z_e,z_h)$ at the boundary of the barrier and the n-type GaAs layer:

$$\psi_i(\mathbf{r}_\parallel,z_e=d,z_h) = \int A(\mathbf{k}_r)\psi_f(\mathbf{r}_\parallel,z_e=d,z_h)d\mathbf{k}_r\,, \quad (20)$$

From this equation, we get

$$A(\mathbf{k}_r) = 2\frac{8a_B}{\sqrt{2\pi}(4+a_B^2k_r^2)^{3/2}}\,\psi_e(z_e=0)\,\exp(-b/2)\,. \quad (21)$$

The tunneling rate is

$$\frac{1}{\tau_{\rm ex}} = \int|A(\mathbf{k}_r)|^2\,\frac{\hbar k_{ez}}{m_e}\,d\mathbf{k}_r = \int\frac{(8a_B)^2}{2\pi(4+a_B^2k_r^2)^3}\,\frac{4}{w}\exp(-b)\,\frac{\hbar k_{ez}}{m_e}\,d\mathbf{k}_r. \quad (22)$$

By comparing Eqs. (14) and (22), we get the matrix element

$$|M_{\rm ex}(k_r)|^2 = \frac{2^8(2\pi)^2a_B^2\hbar^4k_{ez}^2}{m_e^2w(4+a_B^2k_r^2)^3}\exp(-b)\,. \quad (23)$$

Note that k_{ez} and k_r are related by the resonant tunneling condition (5).

Before finishing the derivation of the tunneling current, we need to outline the classification of formed excitons. Due to electron-hole exchange interaction, noninteracting QW exciton should be described in terms of the z-component of its total angular momentum, rather than the individual z-components of the electron and hole angular momentum. However, the hole spin-orbital interaction combined with QW confinement effect results in a mixing of light-hole (LH) and heavy-hole (HH) exciton states with different z components of exciton angular momentum[16] (compare with a similar mixing of HH and LH states of a QW hole when $k_{h\parallel} \neq 0$)[17]. But we may still classify excitonic states in terms of LH and HH excitons at small $k_{\mathrm{ex}\parallel}$ where the mixing of LH and HH states is small.

The electron-hole exchange interaction (of both short-range exchange interaction and longitudinal transverse splitting[18]) splits the QW LH and HH exciton levels into four close sublevels each.[19] Of the total eight sublevels, six correspond to the excitons in a mixed state, with both spin singlet and spin triplet parts. These excitons can relax to $k_{\mathrm{ex}\parallel} = 0$ by phonon scattering and then radiatively decay. Excitons at the other two sublevels (one for LH and one for HH excitons) are paraexcitons (i.e., their spin states are pure triplets). Paraexcitons are not radiatively active, so they are first converted into optically active excitons (by means of exciton-exciton and exciton-free carrier interaction) and then radiatively decay. One-quarter of the total created LH and HH excitons are paraexcitons.

An alternative scenario for both types of excitons is for them to dissolve into a free electron and a subband hole by the electron tunneling back to the n-type GaAs layer from the QW. We have estimated that the typical exciton lifetime set by the back-tunneling process is about 50 ps, which is much longer than the typical exciton conversion, relaxation, and radiative recombination lifetime ($\sim$ 10 ps). Therefore, the exciton population inside the QW is negligibly small, and the net exciton tunneling current is approximately given by the forward tunneling current.

To get the total tunneling current density J_{ex} into one exciton level, we integrate the tunneling rate 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, and get

$$J_{\mathrm{ex}} = \frac{m_e}{(2\pi)^4\hbar^3} \int d\mathbf{k}_{e\parallel} \int d\mathbf{k}_{h\parallel} \frac{|M_{\mathrm{ex}}(k_r)|^2}{k_{ez}} \times f_e(\mathbf{k}_{e\parallel}, k_{ez})\, f_h(\mathbf{k}_{h\parallel}, E_{hz}) \,. \tag{24}$$

In Eq. (24), we can change the integration variable from $\mathbf{k}_{e\parallel}$ and $\mathbf{k}_{h\parallel}$ to $\mathbf{k}_{\mathrm{ex}\parallel}$ and $\mathbf{k}_r$ by expressing $\mathbf{k}_{e\parallel}$ and $\mathbf{k}_{h\parallel}$ in terms of $\mathbf{k}_{\mathrm{ex}\parallel}$ and $\mathbf{k}_r$. Since the integrand only depends on the magnitudes of $k_{\mathrm{ex}\parallel}$ and k_r, and the angle θ between $\mathbf{k}_{\mathrm{ex}\parallel}$ and $\mathbf{k}_r$, we simplify Eq. (24) to

$$J_{\mathrm{ex}} = \int k_{\mathrm{ex}\parallel}\, dk_{\mathrm{ex}\parallel} \int k_r\, dk_r \int d\theta\, \frac{m_e}{8\pi^3\hbar^3} \frac{|M_{\mathrm{ex}}(k_r)|^2}{k_{ez}} \times f_e(k_{\mathrm{ex}\parallel}, k_r, \theta)\, f_h(k_{\mathrm{ex}\parallel}, k_r, \theta) \,. \tag{25}$$

Before we calculate J_{ex} numerically, let us estimate the peak value of J_{ex} as compared to that of J_e. Since $k_r \sim 1/a_B$, from Eq. (23), we have $|M_{\mathrm{ex}}|^2 \sim 2\pi a_B^2 |M_e|^2$. From Eq. (25), we get

$$J_{\mathrm{ex}} \sim 2\,\pi a_B^2\, N_h\, J_e \,. \tag{26}$$

Where N_h is the 2D hole density inside the QW. For $\pi a_B^2\, N_h \sim 0.1$, the ratio of J_{ex} over J_e is about 0.2. Hence J_{ex} is comparable in magnitude with J_e.

Figure 2 shows the calculated tunneling current density as a function of the effective bias V_a for $T = 0$ K and $T = 4$ K. The QW is 50 Å wide, and the $Al_{0.3}Ga_{0.7}As$ barrier is 100 Å wide. The 1s HH exciton binding energy E_{ex} in the QW is about 12 MeV.[20] The electron Fermi level in the n-type GaAs layer is 3 MeV above the conduction band edge, and the hole Fermi level in the QW is 1 MeV below the first hole subband edge in the QW, corresponding to $\pi a_B^2\, N_h \sim 0.08$. The second current peak represents the normal resonant tunneling of electrons into the first electron subband in the QW. The first current peak corresponds to the resonant tunneling into the 1s HH-exciton level below the first electron subband. We have neglected the fine structure of exciton tunneling current due to the exciton level splitting, since

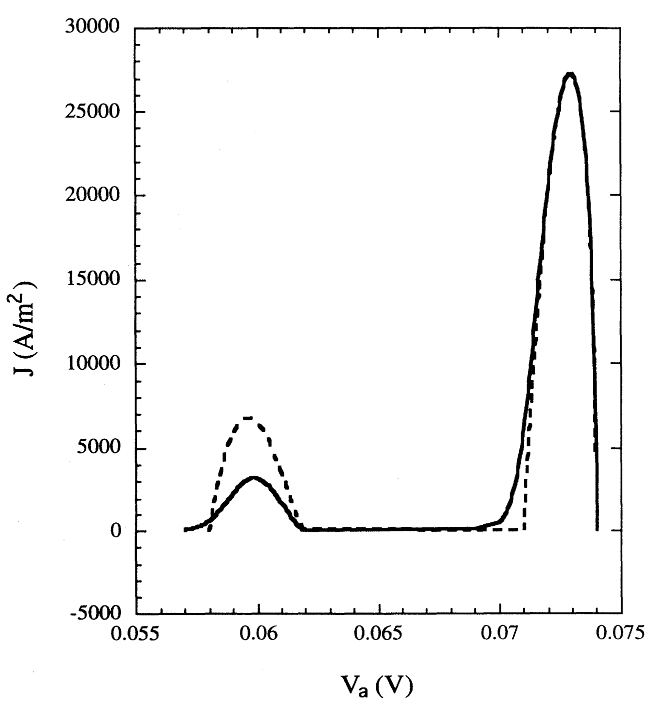

FIG. 2. Numerically calculated tunneling current density as a function of bias at $T = 0$ K (dashed line) and $T = 4$ K (solid line).

the splitting is quite small. From Fig. 2, we see that the ratio of the peak value of J_{ex} over that of J_e is about 0.25 at $T = 0$ K. The width of J_{ex} is slightly broader than the width of J_e, which agrees with our qualitative prediction from the resonant tunneling condition. Figure 2 also shows that at finite temperature, J_{ex} has a tail in the low bias side, meanwhile its peak value decreases.

We can estimate the asymptotic behavior of J_{ex} on the upper and lower limit of the bias V_a using (24). When V_a approaches its upper limit $V_{max} = (E_{ez} - E_{ex})/e$, the z-direction velocity $\hbar k_{ez}/m_e$ of electrons which can tunnel in, approaches zero since it is proportional to $(V_{max} - V_a)^{1/2}$. Since $k_r \leq \sqrt{2\mu(E_{ez} - E_{ex} - eV_a)}/\hbar, k_r$ also goes to zero. This means electrons can only combine with holes with same lateral velocity to form excitons. Both restrictions lead to the asymptotic behavior $J_{ex} \sim (V_{max} - V_a)^{3/2}$.

On the other hand, when V_a approaches its lower limit [Eq. (7)] at $T = 0$ K, both the number of electrons and holes which can combine to form excitons approaches zero as $V_a - V_{min}$. Besides, the total transverse momentum of electron-hole pair also goes to zero because the energy conservation only allows small $k_{ex\|}$. Therefore,

$$J_{ex} \sim \begin{cases} (V_a - V_{min})^2 & \text{if } k_{Fe} > k_{Fh} \\ (V_a - V_{min})^{5/2} & \text{if } k_{Fe} < k_{Fh}\ . \end{cases} \tag{27}$$

The extra factor $(V_a - V_{min})^{1/2}$ at $k_{fe} < k_{Fh}$ appears because the z-component velocity of tunneling electrons is proportional to $(V_{max} - V_a)^{1/2}$ in this case. The asymptotic behavior of J_{ex} is different from that of J_e due to its two-particle nature.

From Eq. (25), we can easily get the initial transverse **k**-vector ($k_{ex\|}$) distribution $f(k_{ex\|})$ of excitons formed by hole-assisted electron resonant tunneling before thermalization

$$f(k_{ex\|}) \propto k_{ex\|} \int dk_r \, \frac{k_r \, |M_{ex}(k_r)|^2}{k_{ez}} \times \int d\theta \, f_e(k_{ex\|}, k_r, \theta) \, f_h(k_{ex\|}, E_r, \theta)\ . \tag{28}$$

Figure 3 shows the initial exciton $k_{ex\|}$ distribution $f(k_{ex\|})$ under two different bias at $T = 4$ K. We can see that at lower bias (dashed line), more excitons are formed with smaller transverse momentum. As we know, excitons with small $\Delta k_{ex\|}$ have a large spatial coherence, leading to superradiative decay.[4] For example, for excitons with $k_{ex\|} \leq 3 \times 10^7$ m^{-1}, have a spatial coherence radius of 300 Å and their radiative decay rate is one order of magnitude larger than the exciton without spatial coherence.[22] Figure 4 shows the percentage of excitons created with spatial coherence radius larger than 300 Å. At $T = 0$ K, the percentage increases to 100% at low enough bias, while at $T = 4$ K the percentage is saturated at about 50% under low bias.

Unfortunately, the superradiative decay of excitons with spatial coherence radius larger than 300 Å is still slower than the rapid thermalization due to the phonon

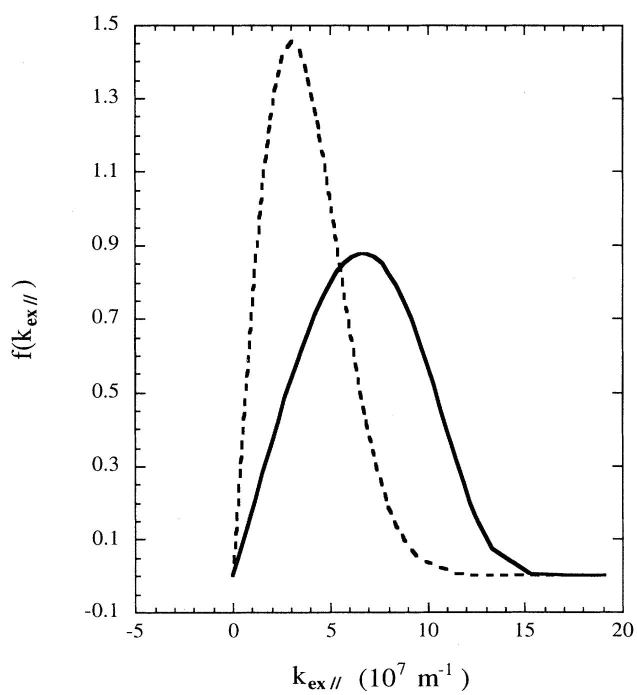

FIG. 3. The transverse **k**-vector distribution of QW excitons formed by hole-assisted electron resonant tunneling at $T = 4$ K under two bias: $V_a = 0.054V$ (dashed line) and $V_a = 0.061V$ (solid line).

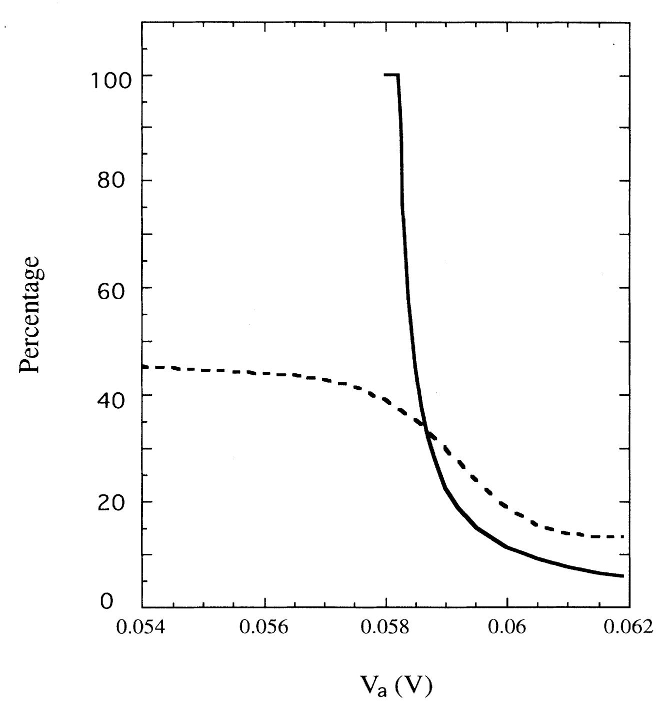

FIG. 4. The percentage of excitons created by hole-assisted electron resonant tunneling with $k_{ex\|} \langle 3 \times 10^7$m^{-1} at $T = 0$ (solie line) and $T = 4$ K (dashed line).

scattering and free carrier scattering at $T = 4$ K. In order to make the superradiative decay of most created excitons beat their thermalization process at $T = 4$ K, the bias has to be extremely low and consequently the tunneling current is also very small.

V. CONCLUSION

In summary, we have demonstrated a resonant tunneling process: the direct creation of QW excitons through hole-assisted electron resonant tunneling. The current density of this tunneling process is on the same order of magnitude as the conventional electron resonant tunneling current density. However, the two-particle nature of this tunneling process makes it different from the ordinary one-particle (electron, hole or exciton) tunneling process in both the resonant tunneling condition, and the asymptotic behavior in the upper and lower limit of the bias.

In addition to its own interest as a physical process, the direct creation of QW excitons by hole-assisted electron resonant tunneling can be utilized to make an electrical current driven excitonic optoelectronic device and to explore excitonic cavity quantum electrodynamics.[21]. It would be interesting to investigate the possibility of observing in an electrically pumped p-i-n junction device the cavity QED effects of the low-Q regime, such as increased spontaneous emission coupling efficiency, decreased threshold or thresholdless laser, and cavity enhanced superradiant decay,[1] and effects of the high-Q regime, such as vacuum Rabi-splitting, reversible spontaneous emission, and nonlinear dressed biexcitons.[23,24]

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* Also with NTT Basic Research Laboratories, Atsugishi, Kanagawa, Japan.

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