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Tuning the tunneling probability between low-dimensional electron systems by momentum matching

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We demonstrate the possibility to tune the tunneling probability between an array of self-assembled quantum dots and a two-dimensional electron gas (2DEG) by changing the energy imbalance between the dot states and the 2DEG. Contrary to the expectation from Fowler-Nordheim tunneling, the tunneling rate decreases with increasing injection energy. This can be explained by an increasing momentum mismatch between the dot states and the Fermi-circle in the 2DEG. Our findings demonstrate momentum matching as a useful mechanism (in addition to energy conservation, density of states, and transmission probability) to electrically control the charge transfer between quantum dots and an electron reservoir. © *2015 AIP Publishing LLC*.
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Since the invention of the Esaki diode[1] in 1957, tunneling has been used as a versatile transport mechanism to tune the electronic properties of semiconductor nanostructures. As the Esaki diode demonstrates, the tunneling current can be tuned by adjusting the *density of states* of the system into which the tunneling carriers will be injected. Another common mechanism that affects the bias-dependent tunneling current is the modification of the barrier *transmission probability* as demonstrated in Fowler-Nordheim tunneling.[2] Finally, the tunneling current is strongly affected by the *overlap of the wave functions in real space* of injector and collector, a fact that lies, e.g., at the core of scanning tunneling microscopy.[3]

Here, we demonstrate a somewhat lesser known mechanism to tune the tunneling current in semiconductor devices, i.e., the overlap of the wave functions in momentum space.[4–7] In non-equilibrium tunneling between self-assembled InAs quantum dots and a two-dimensional electron gas in GaAs, we find that with increasing energy imbalance, the tunneling current strongly decreases. This effect can be well explained by an increasing momentum mismatch between the injector and collector. It is strong enough to supersede the exponential increase of the transmission probability through the tunneling barrier, caused by the decreasing barrier height with increasing injection energy.

The investigated semiconductor device consists of a layer of self-assembled InAs quantum dots, separated by a tunneling layer from an inverted, modulation doped two-dimensional electron gas in a GaAs/(AlGa)As heterostructure. The samples were grown by molecular epitaxy on a semi-insulating GaAs(001) substrate. The active layers of the structure are as follows: 300 nm $Al_{0.34}Ga_{0.66}As$, a Si delta doping layer, followed by a 16 nm $Al_{0.34}Ga_{0.66}As$ spacer layer, and a 15 nm GaAs quantum well. Subsequently, 10 nm $Al_{0.34}Ga_{0.66}As$ and 5 nm GaAs were grown as a tunneling barrier. For the quantum dots, approximately 1.9 monolayers of InAs were deposited at 525 °C and covered with 30 nm GaAs. Finally, a 116 nm AlAs/GaAs superlattice blocking layer and 5 nm GaAs cap layer completed the heterostructure. The wafer was cleaved into chips of $4 \times 4\,\mathrm{mm}^2$ size, and field effect transistors were patterned using standard optical lithography and wet chemical etch. Ni/AuGe/Au layers were deposited for Ohmic contacts and Ti/Au for the gate electrode. The device structure and a schematic of the band structure alignment with regard to the Fermi energy are shown in Fig. 1. All measurements were performed at 4.2 K in a cryogen-free cryostat equipped with a superconducting solenoid that can provide magnetic fields of up to 9 T perpendicular to the tunneling direction.

We use a pulsed transconductance spectroscopy technique[8–10] to monitor the tunneling between the quantum dots and the two-dimensional electron gas (2DEG). First, the gate voltage is set to $V_0 = -0.66$ V, so that most quantum dots are filled with one electron each, as determined by capacitance-voltage measurements.[8,11] Then, a gate voltage pulse $V_g < -0.66$ V is applied (see schematic V_g trace in Fig. 1(a)) so that filled quantum dot states are lifted above the Fermi energy and the corresponding electrons can tunnel into the 2DEG. Throughout the measurement, a small voltage is applied between source and drain, and the resulting current I_{SD} is monitored. I_{SD} first decreases as a result of the negative V_g pulse (see Fig. 1(a)) and then gradually increases again as electrons tunnel from the dots into the 2DEG, increasing its carrier density and thus its conductivity (see Fig. 1(c) and Refs. 8 and 10). From a fit to the exponential increase of the conductivity, the tunneling rate Γ from the dots to the 2DEG can directly be determined. The gate voltage pulse height $\Delta V_g = V_0 - V_g$ determines how far above the Fermi energy the electrons are injected into the 2DEG, see green insets in Fig. 2. This energy is given by $\Delta E = e \cdot \Delta V_g / \lambda$, where e is the electron charge and λ is the so-called lever arm,[11] given by

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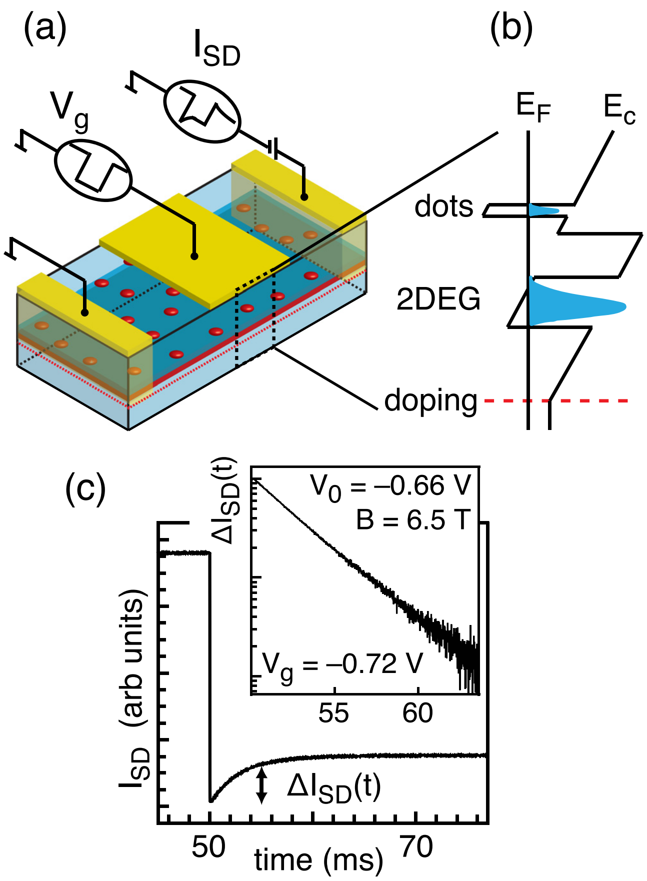

FIG. 1. (a) Schematic of the transistor structure with embedded InAs quantum dots. (b) Schematic representation of the conduction band edge in the active part of the heterostructure. (c) Time dependent trace of the source-drain current I_{SD}. When a negative voltage pulse is applied to the gate (see (a)), I_{SD} first abruptly decreases as the carrier density in the 2DEG decreases. Then, more gradually, I_{SD} increases again as electrons tunnel out of the quantum dot layer into the 2DEG. The corresponding time constant is determined from the exponential increase in I_{SD} (see inset).

the distance between the 2DEG and the gate, d_{gate}, divided by the distance between the 2DEG and the dots, d_{dots}. Here, $\lambda = d_{gate}/d_{dots} = 7$.

The data points in Fig. 2 show the measured tunneling rate as a function of the pulsed gate voltage V_g. With

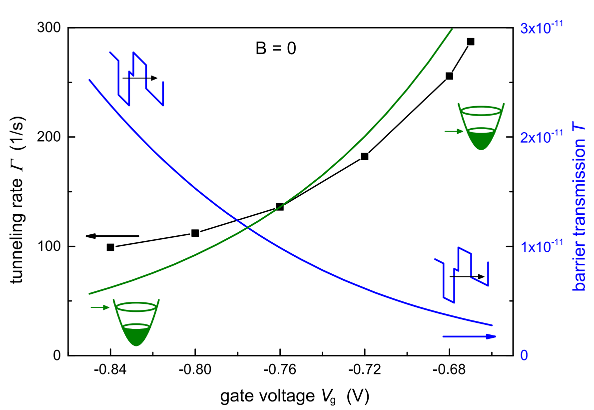

FIG. 2. Black data points: Experimentally determined tunneling rate from the quantum dot states into the 2DEG as a function of the pulsed gate voltage. Blue curve: Barrier transmission coefficient through the tunneling barrier (see Fig. 1(b)), calculated using a WKB approach. Green curve: Calculated effect of the momentum mismatch between the quantum dot states and the states in the 2DEG on the tunneling rate.

increasing energy above the Fermi energy (decreasing V_g), a pronounced decrease of the tunneling rate is observed. Between $\Delta E \approx 0$ ($V_g = -0.67$ V) and $\Delta E = 24$ meV ($V_g = -0.84$ V), Γ decreases by almost a factor of 3. This is contrary to what is expected from the change in transmission through the tunneling barrier (see blue insets in Fig. 2). For comparison, the blue line in Fig. 2 shows the transmission through the tunneling barrier (see Fig. 1(b)), calculated using a simple WKB approach. As expected from Fowler-Nordheim tunneling, the transmission increases as the energy of the dots is lifted higher above the Fermi energy in the 2DEG. Here, again, the factor is about 3. Therefore, in total, the mechanism that governs the bias dependent tunneling current is estimated to change the tunneling rate by roughly one order of magnitude between $\Delta E = 0$ and $\Delta E = 24$ meV.

This decrease in the tunneling rate cannot be explained by a change in the density of states in the collector either. A 2DEG with a single occupied subband has a constant density of states. If, for any reason, a second subband should become available at higher energies, this would increase the tunneling rate rather than decrease it.

We therefore propose that the mechanism that dominates the tunneling rate is the decreasing overlap between the wave functions of the quantum dots and the 2DEG in momentum-space. This is schematically shown in the left insets of Fig. 3, where the ground state wave functions in quantum dots in *k*-space are depicted by Gaussians and the Fermi surface of the 2DEG is indicated as a circle.[10] When the gate voltage pulse is decreased from $V_g = -0.67$ V (top curve) to $V_g = -0.84$ V (bottom curve), the radius of the Fermi circle (i.e., circle in momentum space that corresponds to the energy of the states in the quantum dot) increases—see also insets in Fig. 2. Therefore, the overlap between the wave functions in the dot and the 2DEG decreases, which

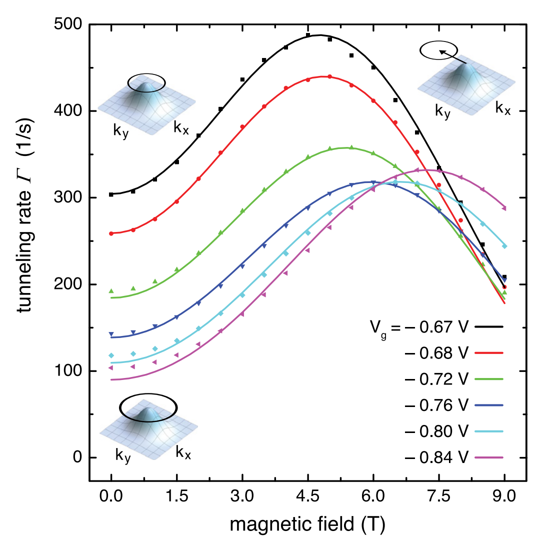

FIG. 3. Measured tunneling rates as a function of a magnetic field, applied perpendicular to the tunneling direction, for different pulsed biases V_g (data points). Solid lines show fits to the data, using the model in Ref. 10. Left two insets depict how the radius of the Fermi circle in the 2DEG increases with decreasing V_g. Gaussian surfaces represent the wave function of the dot in momentum space. Top two insets indicate the effect of the magnetic field, which shifts the Fermi circle with respect to the dot wave function.

can qualitatively explain the reduction in the tunneling rate with decreasing V_g.

For a more quantitative assessment, we use magneto-tunneling spectroscopy[10,12–19] to evaluate the overlap in momentum space between the dots and the 2DEG. As sketched in the right inset of Fig. 3, a magnetic field B, applied perpendicularly to the tunneling direction, adds a contribution of $\Delta k = eB\Delta z/\hbar$ to the momentum of the tunneling electron. Accordingly, the Fermi circle will shift by this amount with respect to the momentum of the quantum dots (see arrow in the right inset of Fig. 3). Therefore, with increasing magnetic field, the overlap will first increase, as the Fermi circle approaches the peak of the wave function and then decrease again as it shifts past the maximum. This is what we observe in the experiment (data points in Fig. 3). From a fit of the data to an analytical model of the tunneling process (solid lines in Fig. 3), we can obtain the dimensions of the quantum dots as well as the Fermi wave vector k_F of the final states in the 2DEG (for details, see Ref. 10). We find that k_F increases from $2.05 \times 10^8\,\mathrm{m}^{-1}$ at $V_g = -0.67\,\mathrm{V}$ to $2.90 \times 10^8\,\mathrm{m}^{-1}$ at $V_g = -0.84\,\mathrm{V}$, which corresponds to a change in Fermi energy of 23 meV. This is in good agreement with the expected change in energy, $\Delta E = 24\,\mathrm{meV}$, derived above using the lever arm approach. We also find that the dots are somewhat elongated (3%–15%), in agreement with our previous findings.[10,20] Furthermore, the simulations show that with increasing imbalance between the back contact and the 2DEG ($V_g = -0.67\,\mathrm{V} \rightarrow V_g = -0.84\,\mathrm{V}$), the effective dot size decreases from ≈ 7 nm to ≈ 6 nm. This can also be understood as an effect of the momentum matching: At high imbalance, the Fermi circle has a comparably large diameter, so that states from smaller dots with a broader wave function in k-space have a higher tunneling probability than states in larger dots. This shifts the effective dot size, as obtained from the fits to the data in Fig. 3, towards smaller dots, when the pulsed gate voltage is decreased. Note that the observed change in dot size corresponds to an inhomogeneous broadening of the ground state energy of roughly 7 meV, in agreement with estimates from capacitance voltage measurements.

In order to assess, whether momentum matching can also quantitatively explain the data in Fig. 2, we calculated the tunneling rate as a function of the gate voltage, following the approach by Chuang and Holonyak.[21] For the wave functions in the quantum dots, we used the now well-established model of a slightly elliptical, parabolic confinement.[10,20,22] The results, normalized with respect to the data point at $V_g = -0.76\,\mathrm{V}$, are shown as the green curve in Fig. 2. While the general trend of the data can be well accounted for by our model calculations, there are still significant discrepancies between the data and the model. These can be understood as follows. First, in the model of Ref. 21, the change of the barrier transparency with changing gate voltage is not taken into account, which will increase the tunneling rate at lower bias and decrease it at higher bias, as shown by the WKB-calculations (blue curve in Fig. 2). Second, as mentioned above, small dots are favored at high negative bias, which will also lead to an increased tunneling rate. Considering these additional factors, we believe that the agreement between the experiment and the model calculations is satisfactory and shows that momentum matching can be used as a tool to tune the tunneling probability between quantum dots and a 2DEG as a carrier reservoir.

Our findings may be of technological interest. Indeed, momentum matching between tunnel-coupled 2DEGs has been studied for more than 30 years, and active devices, based on this mechanism have been proposed.[4,5] Recently, this research has received much attention because of the availability of coupled graphene heterostructures.[6,7] Magnetic-field-induced momentum matching between a (two-dimensional or three-dimensional) electron gas and quantum dots has shown to be a versatile tool to study detailed properties of the quantum dot states.[10,18,19] The necessary high magnetic fields, however, make this technique unsuitable for electronic applications. In the present study, we demonstrate how momentum matching can be used to tune the tunneling between quantum dots and a reservoir, using all electrical means. Such a tunability, on the other hand, is an important prerequisite for realizing quantum dot memory devices, which combine the advantages of both FLASH memory and DRAM.[23,24] Only when the tunneling rate into and out of the quantum dots can be tuned over a wide range, it is possible to achieve both long retention time (as in FLASH memories) and at the same time fast write and readout times (as in DRAM).

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