Fermi-Edge Singularity in Resonant Tunneling

A. K. Geim, P. C. Main, N. La Scala, Jr., L. Eaves, T. J. Foster, P. H. Beton, J. W. Sakai, F. W. Sheard, and M. Henini
Department of Physics, University of Nottingham, Nottingham NG7 2RD, England

G. Hill and M. A. Pate
Department of Electrical and Electronic Engineering, University of Sheffield, Sheffield S1 3JD, England
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We have observed a Fermi-edge singularity in the tunneling current between a two-dimensional electron gas (2DEG) and a zero-dimensional localized state. A sharp peak in the tunnel current is observed when the energy of the localized state matches the Fermi energy of the 2DEG. The peak grows and becomes sharper as the temperature is decreased to our lowest temperature of 70 mK. We attribute the singularity to the Coulomb interaction between the tunneling electron on the localized site and the Fermi sea.

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The Coulomb interaction between conduction electrons leads to various anomalies in the properties of a metal which involve the energy spectrum near the Fermi energy (ε_F) [1]. X-ray absorption in metals shows a Fermi-edge singularity (FES) which has become known as the Mahan-Nozières-Dominicis (MND) singularity [2]. More recently, there has been much interest in a similar anomaly seen at low temperatures in the optical spectra of doped semiconductors [3]. The current in a tunneling system may also be influenced by electron-electron interactions and a number of mechanisms have been proposed which could lead to singularities at ε_F (for references, see [4]). In the last few years it has been suggested that tunneling through a quantum dot may emerge as a new tool for studying electron-electron interactions. FES has been predicted due to either on-site Coulomb repulsion of electrons with different spins (Kondo resonance) [5,6] or the interaction between a tunneling electron and the Fermi sea in the contacts [7]. Although a large number of effects due to single electron transport and Coulomb blockade phenomena have been seen in metallic and semiconducting submicron tunneling devices [8], no evidence for a Fermi-edge singularity has been reported to date.

In this Letter we report the observation of a Fermi-edge singularity in resonant tunneling between a two-dimensional electron gas (2DEG) and a strongly localized zero-dimensional (0D) state. To investigate the 0D-2D tunneling process we have employed our recent observation that the onset of the tunnel current in mesoscopic and also conventional, macroscopic resonant tunneling devices (RTD) is determined by tunneling through random impurity-related states in the quantum well [9]. Our technique is an alternative to the nanofabrication of quantum dots [8] and provides much more strongly confined 0D states. The double barrier RTDs were grown by molecular beam epitaxy on n^+GaAs substrates with substrate temperatures between 480 and 550 °C to inhibit donor segregation from the doped contact regions into the active region of the device [10]. The thickness of both $(Al_{0.4}Ga_{0.6})As$ barriers is 5.7 nm, the quantum well width is 9 nm, and there is a 20 nm spacer layer between each barrier and the more heavily doped contact regions. We also grew samples in which the center plane of the quantum well was δ doped by Si donors with concentrations between 2×10^{13} and 8×10^{13} m^{-2}. Square mesas of side lengths varying between 6 and 100 μm were fabricated using photolithography. For further details we refer to our previous papers [9].

Figure 1 shows a schematic energy band diagram for our devices under bias. A current flows when the energy of an electron in the emitter 2DEG is resonant with a state in the quantum well [11]. The inset in Fig. 2 shows the main resonance due to the lowest 2D subband in the quantum well. The large (20:1) peak-to-valley ratio indicates the high quality of our structures. At biases below the main resonance near the onset of the tunnel current we have found an additional steplike structure which is shown in Fig. 2 ($V > 70$ mV) for one of the undoped samples. Similar structure is seen in all devices, although

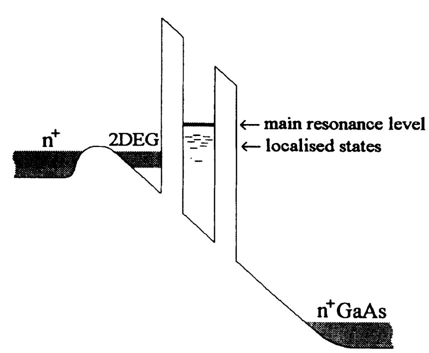

FIG. 1. Schematic diagram of the conduction-band profile of our devices under bias. Tunneling occurs from a two-dimensional electron gas through the ground state in the quantum well (for the main resonance) or highly localized impurity levels at lower energies.

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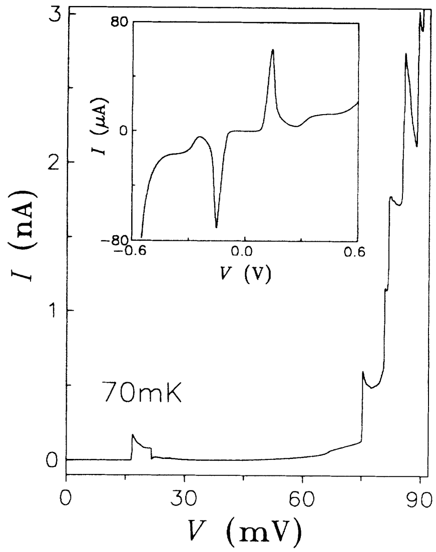

FIG. 2. $I(V)$ characteristic at low bias for a device 12 μm across. The inset shows the main resonance.

details are unique to a particular device, and features occur in both directions of the applied bias but differ in their exact form. In the δ-doped samples the additional features are more numerous and extend to lower values of applied bias. In many of the undoped devices isolated peaks occur such as that shown in Fig. 2 for $V \cong 20$ mV. We consider the additional features to be due to tunneling through localized 0D states in the quantum well of the RTD with energies well below the edge of the lowest 2D subband as shown schematically in Fig. 1 [9,12].

Two examples of the step structure in $I(V)$ characteristics are plotted in Fig. 3. In Fig. 3(a) we show in more detail the isolated peak of Fig. 2 and Fig. 3(b) is the current onset for a δ-doped RTD with 2×10^{13} m^{-2} Si donors in the quantum well. The unexpected feature in the observed $I(V)$ dependences is the singular enhancement of tunneling near the threshold (see Figs. 2 and 3), when the localized state is resonant with the emitter Fermi energy. Note that every current step in Fig. 2 is accompanied by such an enhancement. The characteristic width (full width at the half height) of the threshold peaks can be as small as 0.2 mV at the lowest temperature [e.g., see the marked feature in Fig. 3(b)]. The low voltage edge of each step is thermally activated down to 70 mK indicating that the 2DEG remains in thermal equilibrium with the main heat bath. In general, as in Fig. 3(b), there is some additional oscillatory structure within the step at voltages above the threshold voltage V_{th}. However, in contrast to the singularity this structure does not depend on temperature. The Fermi-edge singularity is seen in *all* devices at temperatures below 1 K.

The general behavior of the impurity-assisted tunneling, i.e., without the singularity, can be understood as follows. Under a typical applied bias of tens of mV, the tunnel current in our devices is limited by tunneling

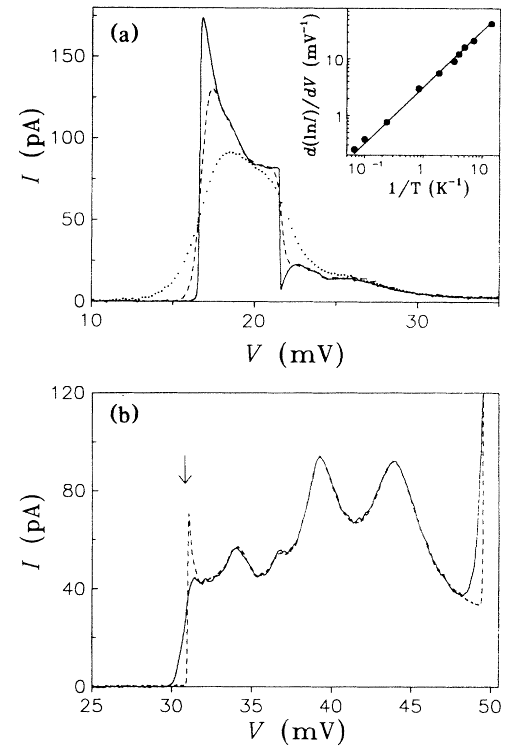

FIG. 3. Detailed $I(V)$ characteristics at low biases when the first localized level is resonant with the emitter 2DEG. (a) The same device as in Fig. 2 at three different temperatures of 70 mK (solid line), 1.3 K (dashed line), and 5 K (dots); (b) another device 6 μm across and under opposite bias at 70 mK (dashed line) and 1.2 K (solid line). Inset: Temperature dependence of the logarithmic slope of the tunnel current near the threshold voltage. The solid line corresponds to $\alpha = 0.27$.

through the emitter barrier and the states in the quantum well are empty most of the time [13]. As the bias increases, the impurity level moves downwards relative to the energy of the emitter 2DEG (see Fig. 1) and the tunnel current exhibits a step increase when the localized state coincides with the Fermi energy. As the voltage is increased further and the energy of the 0D state becomes lower than the lowest energy state of the emitter, no states are available for resonant tunneling and the current falls sharply [see Fig. 3(a)]. In Fig. 3(b) a second impurity channel comes in resonance with the 2DEG (at $V \simeq 50$ mV) before the first channel has passed away. The latter behavior is also seen above 75 mV in Fig. 2. The tunnel current is given by [11]

$$I = (e/\hbar)\Gamma_e(\varepsilon_i)\theta(\varepsilon_i)f(\varepsilon_i)\,, \qquad (1)$$

where $f(\varepsilon) = \{1+\exp[(\varepsilon-\varepsilon_F)/k_BT]\}^{-1}$ is the Fermi-distribution function, $\theta(\varepsilon)$ is the unit step function, and ε_i is the energy of a 2DEG state resonant with the impurity state, measured from the bottom of the 2DEG subband. The 2D-0D tunneling coefficient Γ_e can be written as [13]

$$\Gamma_e(\varepsilon_i) = t\exp(-\varepsilon_i/\varepsilon_0)\,, \qquad (2)$$

where ε_0 is the binding energy of the localized state and t is a coefficient which includes parameters of the localized state and the tunnel barrier but is independent of the kinetic energy ε_i of tunneling electrons within a 2DEG subband. Near the onset of the tunnel current, Eq. (1) varies as the Fermi function which fits very well to the observed $I(V)$ characteristics. $I(V)$ curves for different temperatures intersect at the same point [e.g., see Fig. 3(a)], consistent with the case of 2D-0D tunneling. To convert the voltage across the device into an energy scale, we use $\varepsilon_F-\varepsilon_i=\alpha(V-V_{\text{th}})$ where the constant α is characteristic of the distribution of electrostatic potential across the device [11]. Experimental curves yield $\alpha=0.25\pm0.05$ for all devices. The inset in Fig. 3(a) shows an example of the temperature dependence of the tunnel current below threshold at biases when $I \propto f(\varepsilon_i)\cong\exp[(\varepsilon_F-\varepsilon_i)/k_BT]$ and hence $d\ln(I)/dV\cong\alpha/k_BT$. The linear dependence of the logarithmic slope down to the lowest temperature of 70 mK indicates that the localized state has a very narrow linewidth. This is in agreement with the linewidth $\Gamma_e=\hbar/\tau_e\cong4$ mK expected from the tunneling time $\tau_e=e/I\cong2$ ns which is, in turn, given by the typical value of a current step, $I\cong100$ pA, in our devices [11].

Equation (2) shows that, for noninteracting electrons, the tunnel current within the step varies on the energy scale of the binding energy $\varepsilon_0\cong13$ meV [14] much larger than typical values of the Fermi energy (1-5 meV) in the emitter accumulation layer for the first few steps in the I-V characteristics. Therefore, according to Eqs. (1) and (2), variation of the current within the step is expected to be small as shown by the dashed line in Fig. 4 calculated for the sample in Fig. 3(a). Clearly, the observed singularity in the tunnel current cannot be explained within a model involving only noninteracting electrons. Therefore, we attribute the FES to the influence of the electron-electron interaction.

Three models leading to a FES for the case of impurity-assisted tunneling have been considered recently. First, the interaction between conduction electrons in the emitter 2DEG yields a logarithmic singularity in the tunneling density of states [4]. Second, repulsion between electrons with the opposite spins on the impurity site may give rise to a Kondo resonance [5,6]. Finally, the interaction between an electron on the impurity site and the Fermi sea in the emitter contact may cause the MND singularity [7]. The first effect is important if the electron mean free path is short but is expected to be negligibly small for our 2DEG at the emitter interface. In addition, we would expect a negative contribution to the tunnel current near ε_F rather than the increase which is observed [4]. The Kondo resonance also leads to $I(V)$ qualitatively different to that observed [6]. The FES in our experiments is very similar to the behavior predicted by Matveev and Larkin (ML) [7]. The singularity originates from extra tunneling processes due to the Coulomb interaction between the fluctuating charge on the localized site and the Fermi sea in the contacts. The interaction allows an electron to violate the requirement of energy conservation between its initial and final states and the electron can tunnel into the localized site from an initial state which does not contribute in a model of noninteracting particles. The difference in the energies is transferred to or from the Fermi sea. A singularity arises at ε_F because scattering processes with small energy transfer are most effective (Fermi's golden rule) while the Pauli principle allows them only near ε_F. The ML theory yields a power-law singularity of the form [7]

$$I\propto(\varepsilon_F-\varepsilon_i)^{-\beta}\theta(\varepsilon_F-\varepsilon_i),\quad \beta\cong(3/8\pi^2)\lambda_F/d\,, \tag{3}$$

where λ_F is the Fermi wavelength. We estimate the distance from the plane of the 2DEG to the localized site (d) to be $\cong25$ nm assuming the Fang-Howard approximation for the emitter 2DEG. Then, for the first few steps, which occur at biases between 15 and 80 meV, we expect β to be in the range 0.1-0.25. The interaction lasts for a finite time, τ_c, before an electron escapes from the impurity state into the collector contact. This leads to smearing of the singularity on the energy scale $\Gamma_c=\hbar/\tau_c$ as given by [7]

$$I\propto\left[\sqrt{(\varepsilon_F-\varepsilon_i)^2+\Gamma_c^2}\right]^{-\beta}\times\left[\frac{\pi}{2}+\arctan\frac{\varepsilon_F-\varepsilon_i}{\Gamma_c}\right]\theta(\varepsilon_F-\varepsilon_i)\,. \tag{4}$$

We estimate Γ_c in our devices to be of the order 0.1 meV ($\tau_c\cong10$ ps) [13].

To describe the observed form of the FES we assume that the net current includes both single-particle and many-body contributions given by Eqs. (1) and (4), respectively. The absolute value of the many-body current

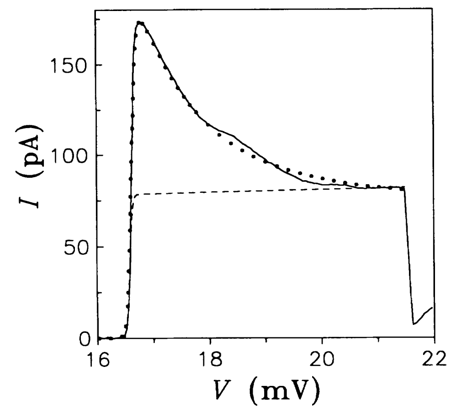

FIG. 4. Comparison of the observed singularity with theory. The solid line is the experimental curve at 70 mK for the same device as in Figs. 2 and 3(a). The dotted curve is the behavior expected from the ML theory. Dashed curve: If the electron-electron interaction is neglected, the tunnel current within the step exhibits only a very small increase with increasing bias.

in Eqs. (3) and (4) is unknown and is used as a fitting parameter. Also, we allow Γ_c to vary around 0.1 meV to obtain the best agreement with the experimental data. Figure 4 shows the best fit to the low-temperature $I(V)$ characteristic from Fig. 3(a). The coefficient β is calculated to be $\cong 0.22$ for this bias and the fit yields $\Gamma_c \cong 0.2$ meV. For other samples, the singularities are also described by values of Γ_c within a factor of 3 of 0.1 meV. For completeness, to describe the observed temperature smearing at the onset of tunneling in Fig. 4 we have multiplied Eq. (4) by the Fermi function $f(\varepsilon_i)$, instead of using the theta function as in Ref. [7]. This allows us to fit the $I(V)$ curves for all temperatures below 1.5 K. For higher temperatures, when $k_B T > \Gamma_c$, the smearing of FES by temperature, in addition to Γ_c, becomes important. Although Fig. 4 shows quantitative agreement between the experiment and ML theory, we note that Eqs. (3) and (4) are derived for biases close to the threshold. In addition, the numerical coefficient $3/8\pi^2$ in Eq. (4) is valid for the case $\lambda_F/d \ll 1$ while we deal with the situation where the interaction is very strong and $\lambda_F/d > 1$ [15].

In conclusion, we have found that the electron-electron interaction has a remarkable effect on tunneling between a degenerate 2DEG and a strongly localized 0D state. A distinct singular feature is observed in the current-voltage characteristics when the Fermi energy matches the energy of the localized state. We attribute this feature to the Coulomb interaction between the fluctuating charge on the impurity site and the 2DEG and describe the results in terms of the ML theory.

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