Formation of Sharp Potential Minima Close to a Quantum Point Contact by Impinging Alpha Particles

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We report the first observation of sharp and spatially localized maxima in the density of a two-dimensional electron gas (2DEG) created by impinging alpha particles. The 5 MeV alpha particles were each found to generate a positive charge in the n^+ doped AlGaAs, which in turn created the potential notch for the 2DEG at the GaAs/AlGaAs interface. This notch was found to decay logarithmically over a time scale of several seconds. The expected profile of the potential minima was roughly determined by the influence the potential had on the conductance of the nearby quantum point contact. Alpha particles hitting within about 5 μm from the point contact could be detected.

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A quantum point contact is understood as a narrow channel for electrons with an integer number of one-dimensional states, which adiabatically merge into a two-dimensional electron gas (2DEG) on each side of the constriction [1]. A smooth parabolic confinement of the constriction gives an excellent description of the quantized conductance for the most regular quantum point contacts. Experimentally, however, a number of deviations from ideal behavior have been found [2]. Thus a nonideal step structure in the conductance versus constriction width (alias gate voltage) is normally ascribed to an irregular confinement curve of the quantum point contact. This irregularity can either be due to the detailed shape of the split gate or due to a charged impurity sitting in the vicinity of the constriction [3]. However, so far detailed comparisons between theory and experiments have not been possible because the potential landscape close to the quantum point contact is not well controlled. A so-called random telegraph noise is often observed in quantum point contacts and related mesoscopic structures [4], where the conductance switches between two or more discrete values reflecting electrons hopping in and out of impurity states. The detailed nature including the spectral density of this type of noise depends crucially on the impurity configuration near the constriction.

We have found a new way of perturbing the potential landscape around a quantum point contact, which allows a much more predictable effect on the conductance versus gate voltage than had earlier been possible. It turns out that impinging 5 MeV alpha particles gives rise to well-defined notches in the 2DEG, which within about 5 μm can be felt in the conductance of the quantum point contact. The potential notch decays away after about 10 s.

Our samples consisted of mesa etched Hall bars made from molecular-beam-epitaxy (MBE) -grown modulation-doped heterostructures with the two-dimensional electron gas embedded 80 nm below the surface. The mobility of the 2DEG was 70 m^2/Vs, and the two-dimensional carrier density was 3.2×10^{15} m^{-2}. Apart from a 15 nm spacer layer the region above the 2DEG was doped with Si, the donor density being $N_d=1.5\times10^{18}$ cm^{-3}. A small fraction of the donors are ionized to deliver electrons to the 2DEG. The split gates, which consisted of two sharp metallized triangles separated by $\sim$0.3 μm, were made by conventional electron-beam lithography. The electrical measurements were performed in a ^{3}He cryostat at temperatures in the range 0.3–1.2 K. The resistance of the samples was measured by small signal lock-in techniques in the current controlled four-probe configuration. After subtraction of a small background the resistance of the quantum point contact was inverted to conductance. When measured as a function of negative gate voltage V_g our samples showed clear conductance quantization in units of $2e^2/h$. The samples were mounted on a chip carrier face to face with an ^{241}Am (5.5 MeV), 40 kBq (1 becquerel=1 s^{-1}) alpha source. The distance between the 2 mm diam alpha source and the sample was 2 mm. When this assembly was immersed in liquid ^{3}He the alpha radiation was efficiently stopped from reaching the heterostructure. However, when the sample was lifted above the ^{3}He surface, it was exposed to alpha radiation. This is seen in Fig. 1, where the conductance of a quantum point contact is plotted as a function of time. The onset and vanishing of the alpha radiation is clearly seen, when the sample is lifted out of the ^{3}He bath and immersed into the ^{3}He bath. The alpha radiation gives rise to random (positive) conductance pulses which decay logarithmically over a time scale of several seconds (Fig. 2). With this method we were able to perform electrical measurements with controlled generation of random pulses in the time regime.

We now turn to discuss how the α particles influence the quantum point contact conductance. The incident alpha particles penetrated $\sim$20 μm into the semiconductor [5], with a substantial generation of electron-hole pairs and impurity ionizations along the trace. Recombination times for electron-hole pairs are extremely short com-

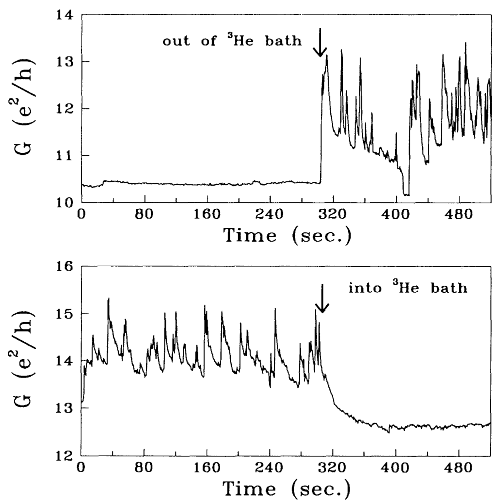

FIG. 1. The conductivity of a quantum point contact plotted vs time, while the sample was immersed and taken up from the ^{3}He bath. The alpha particle radiation was stopped by liquid ^{3}He, which allowed us to switch on and off the alpha particle radiation. It should be noticed that the lower curve was recorded several hours after the upper curve, which gave rise to the shift in conductance between the two curves. The gate voltage applied in the recording of both the two curves was $V_g = -0.7$ V. The temperature was $T = 0.3$ K.

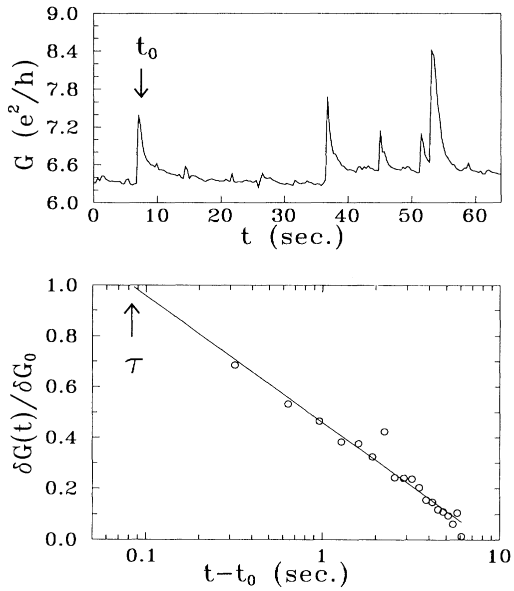

FIG. 2. The alpha particles generated conductivity pulses with positive amplitude (top). The pulse shapes are given by $\delta G(t,r) = \delta G(r,t_0)[1 - A\ln((t-t_0)/\tau)]$, where $\delta G(r,t_0)$ could be related to the distance r between the alpha particle impact site and the constriction. The lower curve shows an example of such a logarithmic decay of a selected pulse. After about 10 s the pulse quickly dies away.

pared to the decay times in our experiments. The conductance pulses originate from impurity ionizations in the doped layer of our heterostructure. The electrons, which are stripped off the ions by alpha particles, are spread over a relatively large volume in the semiconductor. The long decay time is the result of a recombination of ionized donors with electrons trapped in the 2D channel. At low temperatures this recombination is established by tunneling processes through the potential barrier separating the 2DEG and the donors. Such processes are also known from the decay kinetics of persistent photoconductivity and give rise to logarithmic decay of conductance [6]: $\delta G(t)/\delta G(0) = 1 - A\ln(t/\tau)$ for $t \gg \tau$, where τ is the tunneling time for the smallest spatial separation. The difference between persistent photoconductivity and the induced conductivity we report is the local nature of the very small but heavily ionized region created by each alpha particle. At each alpha particle impact site, we expect only a negligible number of Dx centers [7] to be ionized compared to the number of normal Si donors. The permanent increase in the background electron concentration δn due to even a large number of alpha particles is thus much smaller than the concentration in the 2DEG $\delta n/n \ll 1$. An example of our pulse shapes is shown in Fig. 2. Experimentally it was found that one single alpha particle penetrating the sample near the constriction does not change the conductance versus gate voltage characteristic permanently. Only bombardment through several hours may cause a detectable permanent deterioration of the conductance quantization. Thus the major effect of the alpha particles is a temporary perturbation of the confinement potential in the constriction by ionized impurities, which are centered at the alpha particle impact sites.

The quantized conductivity is given by $G = (2e^2/h) \times \sum T_n$, where T_n is the quantum mechanical transmission probability for each of the one-dimensional conductance channels in the constriction [8]. T_n can be calculated from a given confinement potential in the constriction. We use a parabolic saddle potential of the form $\phi(x,y) = 1/2m\omega_y^2 y^2 - 1/2m\omega_x^2 x^2 + \phi_0$ as the approximation to the confinement potential in the constriction. In this configuration the current is passed through the constriction along the x direction. $\hbar\omega_x \simeq 0.3$ meV and $\hbar\omega_y \simeq 1$ meV are the oscillator strengths of the parabolic potential. The transmission probability for this potential is given by [9] $T_n = [1 + \exp(-\pi\epsilon_n)]^{-1}$, where $\epsilon_n = (2/\hbar\omega_x)[E_F - \hbar\omega_y(n + \frac{1}{2}) - \phi_0]$, and E_F is the Fermi energy of the electrons in the broad 2DEG region coupled to the constriction. To linear order a change of confinement potential by $\delta\phi_0$ will produce a change in conductance of

$$\delta G \simeq \frac{2e^2}{h} \sum \frac{dT_n}{d\phi_0} \delta\phi_0 = -\frac{2e^2}{h} \sum \frac{\pi\delta\phi_0}{2\hbar\omega_x} \cosh^{-2}(\pi\epsilon_n/2) . \quad (1)$$

$dT_n/d\phi_0$ achieves its maximum when $\epsilon_n = 0$, i.e., between the conductance steps or in other words, when the transconductance of the device is largest. This is clearly seen in Fig. 3, where the conductance versus gate voltage characteristic was recorded during alpha particle irradiation. A positive point charge Ze placed in the plane of the 2DEG a distance r apart from the constriction will lower the confinement potential by an amount given by the screened Coulomb interaction in two dimensions. In the Thomas-Fermi approximation this potential contribution can be expressed by [10,11]

$$\delta\phi_0(r) = Ze(1+q_s d_0)/4\pi\epsilon q_s^2 r^3 , \qquad (2)$$

where ϵ is the mean value of the dielectric constant of GaAs and vacuum, and $q_s = me^2/2\pi\epsilon\hbar^2 \simeq 4.1\times 10^8$ m^{-1} is the screening constant. In order to justify the application of this two-dimensional result, we note that the thicknesses of the doped layer ($\simeq 2d_0$) and spacer layer are both considerably smaller than the lithographic width of the constriction. Lateral length scales are thus much larger than any vertical dimensions in the problem.

By using Eqs. (1) and (2) we are able to relate a particular conductance pulse amplitude to a distance between the constriction and the associated alpha particle impact site. We assume that the largest pulse amplitudes ($\sim 2e^2/h$) correspond to impact sites within the constriction width. This gives an estimate of the number of positive charges with long lifetimes created by each alpha particle $Z \simeq 224$.

The probability $P(r)dr$ that a particular detected particle has penetrated the sample in the differential length dr around the radius r from the constriction is given by $P(r)dr = 2\pi r\,dr/\pi l^2$, where πl^2 is the effective sampling area of the point contact. The area πl^2 can be obtained from the experimentally determined average pulse frequency $\nu \simeq 9\times 10^{-2}$ s^{-1}, and the pulse frequency per area calculated from the known alpha source strength $\nu/dS = 1.3\times 10^{-4}$ s$^{-1}\,\mu$m^{-2}. This estimate determines the radius of the effective sampling area to $l \simeq 4.7$ μm. This length corresponds to a minimum detectable potential variation of $\delta\Phi_0 \simeq 50$ neV. The corresponding distribution (histogram) of detected conductance changes is then given by $P(\delta G) = P(r)|dr/d\langle\delta G\rangle|$, where $\langle\delta G\rangle = \delta G(r)\{1 + A[1 - \ln(\tau'/\tau)]\} \simeq 0.25\times\delta G(r)$ is the time average of a single pulse. Here τ' is the cutoff time for the logarithmic decay due to the finite thickness of the doped region; $\tau' \simeq 10$ s and $A = 0.21$. The function $r(\langle\delta G\rangle)$ can be obtained from Eqs. (1) and (2). $P(\delta G)$ thus have the form

$$P(\delta G) = a\delta G^{-5/3} , \qquad (3)$$

with

$$a = (2/3l^2)[(0.25Ze/8\hbar\omega_x\epsilon q_s^2)(1+q_s d_0)]^{2/3} = 10.7\times 10^{-4} ,$$

if δG is expressed in units of $2e^2/h$. A fit of Eq. (3) to an experimentally determined histogram shown in Fig. 4 gives $a = 7\times 10^{-4}$. Almost identical results are found for other experimental traces.

The findings we have reported above have several implications, which should be considered in the future. One very interesting aspect of the reported effect is the fact

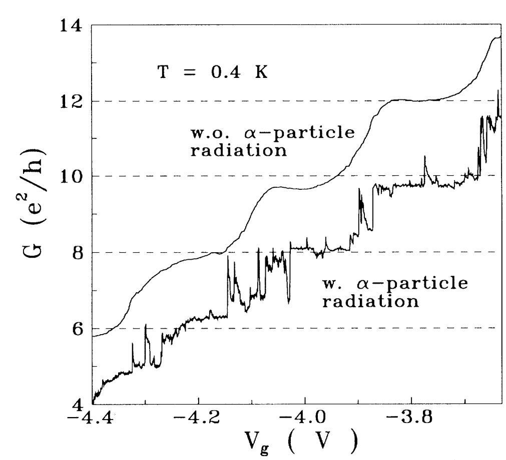

FIG. 3. Conductance measured vs gate voltage at $T = 0.3$ K, while the sample is irradiated by alpha particles (lower curve). The upper curve (shifted $2e^2/h$ for clarity) shows the same measurement with the sample immersed in ^{3}He to stop the alpha particles. The pulses have the largest amplitude between conductance steps in accordance with Eq. (1). The largest pulse amplitudes are of the order $2e^2/h$.

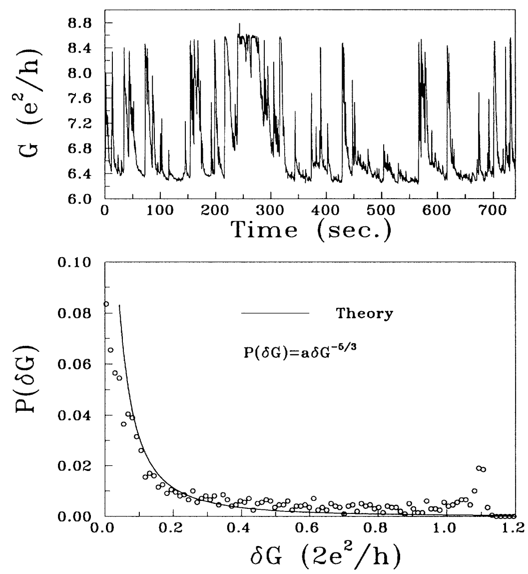

FIG. 4. Top: The random pulse train. Bottom: Normalized histogram of conductance shifts generated from the data in the upper figure (circles), and fitted to the theoretical model given by Eq. (3) (solid line). The fit is produced with $a = 7\times 10^{-4}$. $\delta G = 0$ is chosen at the maximum of the histogram.

that the diameter of the ionized region is very small, $\simeq 0.2$ μm if 10% of the donors along the alpha-particle trace are ionized, and that the potential notch constitutes a quantum dot structure with a potential well, which decays with the radius cubed. The finite lifetime of the quantum dot and the similar appearance of each one of the dots makes them very interesting structures to study. The observation, which is the main content of this Letter, that each quantum dot (potential notch) influences the quantum point contact in an electrostatic manner, which vanishes logarithmically with time, will certainly allow measurements of the conductance versus split gate voltage at different notch potentials. This may lead to a much more detailed picture of the behavior of a point contact subject to a series of well defined potential distributions each at a different time and at various distances from the constriction. Finally there is an interesting application in using the observed effect as a position sensitive detector for high energy particles. We have in fact conducted such experiments and found that three quantum point contacts in a distance of 5 μm respond with different conductance peak amplitudes to an impinging alpha particle. This may allow us to determine the position of the impinging alpha particle in the 2DEG with a precision of about 0.2 μm and over an area of roughly 5×5 μm^2 [12]. Such a spatial resolution is not possible with any other position sensitive detector today.

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