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LETTER TO THE EDITOR

Coherent electron-beam splitting in a two-dimensional electron gas

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Abstract. The possibility of coherent splitting of a ballistic electron beam in a high-mobility two-dimensional electron gas (2DEG) system is discussed. We propose a new version of a planar quantum-point-contact device which is able to produce two coherent and highly collimated divergent beams. The performance of this device is studied by solving the Schrödinger equation of the 2DEG system.

The close analogy between ballistic electron propagation in two-dimensional electron gas (2DEG) systems and classical wave optics has opened a new field of research. The essential features of both light and electron optics are the steering and focusing of a beam. For 2D electrons emitted from a planar point contact, the beam can be focused by magnetic focusing [1], collimation from a smooth constriction [2, 3], tunnel focusing [4] and by an electrostatic lens [5, 6]. In all of these examples the electron beam propagates without loss of phase memory over ballistic distances that can be as large as 100 μm [7]. The coherent splitting of such an electron beam could open new perspectives in the study of quantum interference between alternative carrier paths.

It is the aim of this letter to propose a new version of the planar quantum point contact device [4] which is capable of producing two coherent, highly collimated, divergent beams of ballistic electrons. This electron beam splitter can be fabricated on a GaAs–$Al_xGa_{1-x}As$ heterojunction supporting a high-mobility 2DEG. A schematic picture of the geometry of the device is shown in figure 1. Two metallic gates (A) define a constriction (point emitter) characterized by its width W. Just after the constriction, an independent gate (B) defines a resonant barrier. This resonator could be a square barrier with sharp edges [4] or two narrow barriers placed just outside the constriction (figure 1). The electron beam will split as a consequence interference above the barriers (or resonant tunnelling for barriers higher than the Fermi energy). These resonances have been observed in one-dimensional (1D) electron interferometers [8, 9].

The physics of the splitting effect of the device can be understood by considering a simple picture. When the constriction is small ($\sim \lambda_F$), there is only one propagating mode (i.e. only the first subband is occupied). Then all the ejected electrons have the same wave function (it is in this sense that we speak of a coherent beam). At the end of the constriction, there is strong scattering and the electron wave function of the ejected electrons spreads into many diffracted waves. It is possible to select some

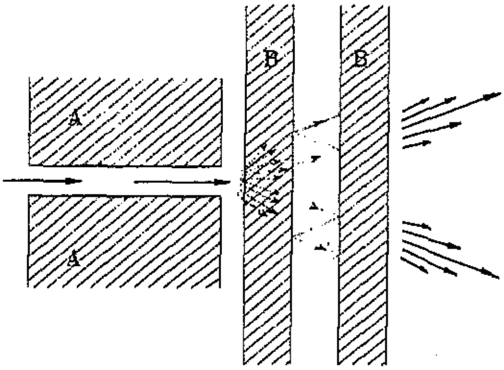

Figure 1. Schematic layout of the proposed device. Two metallic gates (A) define a quantum point contact. Just after the constriction, an independent gate (B) defines a resonant barrier. This potential barrier could be replaced by any potential distribution leading to Fabry–Perot-like resonances.

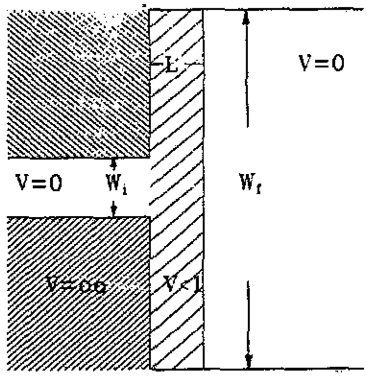

Figure 2. Potential distribution for the two-dimensional calculation.

of these diffracted waves (i.e. those having special angles θ_R) by means of a resonant barrier attached to the point contact.

Let us assume the simplest case of a sharp square barrier with height $V \leqslant 1$ (all the lengths are in units of the Fermi wavelength, λ_F, and the energies are in units of the Fermi energy, E_F, of the electron system). The transmission probability $T(\theta)$ for the electrons at the Fermi level will be a function of the incoming angle θ (measured from the normal to the barrier) and should approximately follow the well known 1D result

$$T(E) = \left\{1 + [V^2/4E(E-V)]\sin^2(2\pi L\sqrt{E-V})\right\}^{-1} \qquad (1)$$

with $E = \cos^2(\theta)$. $T(\theta)$, presents Fabry–Perot resonances at the angles give by

$$\cos^2(\theta_R(n)) = V + \{n/2L\}^2 \qquad (2)$$

where L is the barrier thickness in units of the Fermi wavelength and n is an integer number. For a given L, two highly collimated beams (corresponding to $\pm\theta_R(n=1)$) could be obtained provided

$$(1/2L)^2 < 1 - V < (1/L)^2. \qquad (3)$$

In order to check the validity of this simple picture we have performed a full quantum mechanical calculation of the 2D problem. We assume that the electrons are confined in the transverse direction by hard walls (see figure 2). There are two regions of different widths: W_i simulating the constriction and $W_f (W_f \gg W_i)$ simulating the free 2DEG. A square barrier of length L and height $V \leqslant 1$ is placed just after the constriction. Because of the finite width of the system, the electron transverse momenta are quantized, i.e. $k_{x_i} = n\pi/(W_i)$ and $k_{x_f} = m\pi/(W_f)$. These

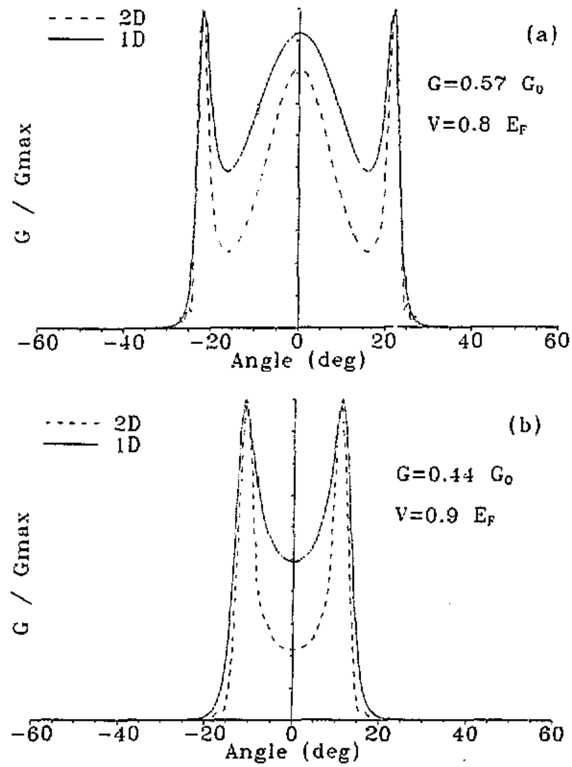

Figure 3. Normalized angular distribution of electrons emitted by a quantum point contact after switching on a square barrier of thickness $L = 2\lambda_F$ and strength (*a*) $V = 0.8E_F$ and (*b*) $V = 0.9E_F$ (broken curves). The total conductance $G = I/V_0$, in units of $G_0 = e^2/(\pi\hbar)$, is also shown. The full curves show the simple 1D results for the normalized transmission probability as a function of the outgoing angle.

transverse modes can be described by an angle $\theta_i = \tan^{-1}(k_{x_i}/k_{zi})$. (Notice that in our units, $k_x^2 + k_z^2 = (2\pi)^2 = k_F^2$ for electrons at the Fermi level.) The total intensity of I, of the emitted electrons can be written as

$$\frac{I}{V_0} = \sum_{\theta_f}\left\{\frac{e^2}{\pi\hbar}\sum_{\theta_i} T_{\theta_i\to\theta_f}(E_F)\right\} = \sum_{\theta_f} G(\theta_f) \tag{4}$$

where V_0 is the small voltage between the left and right electron reservoirs and the summation runs over all the initial (i) and final (f) modes. The transmission probabilities $T_{\theta_i\to\theta_f}(E_F)$ can be obtained by appropriate matching of the wave functions in each region [4, 10, 11].

In figure 3 we present the outcome of our calculations for the current as a function of the outgoing angle $G(\theta_f)$ assuming a constriction width of the order of the Fermi wave length $W_i = 0.95$, $W_f = 30.4$ and a barrier width $L = 2$. In order to make a comparison with the exact 2D calculation, the transmission probablity (1) as a function of the angle is also shown. For $L = 2$ the condition given by the 1D model (3) predicts two diverging beams for barrier heights $0.75 < V < 0.94$, in agreement with our 2D calculations. For barrier heights above 0.94 we get a highly collimated beam in agreement with de Raedt *et al* [4]. This high collimation disappears for lower barriers. As a consequence of the resonances in the transmission probability, the emerging electrons are no longer focused in the forward direction but in the angles defined by the resonances. If the barrier goes below 0.75 a broad peak (not shown) is obtained. As can be seen in figure 3, the angular distribution of the full quantum mechanical calculation follows very closely the expected behaviour obtained with the simpler 1D model. The discrepancy in the relative peak intensities can be easily understood. The diffraction at the constriction edge and the transmission through the barrier are not independent processes (in contrast with our assumptions in the 1D model). The 2D calculation shows that the barrier, so to speak, enhances the diffraction to those angles close to the resonant condition.

We have shown that the proposed device is able to produce an electron beam split into two coherent beams. The basic idea is to use the Fabry–Perot modes of a resonant potential attached to a quantum point contact. We believe that this device can open new perspectives in the study of quantum interference between alternative carrier paths.

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