Unexpected Periodicity in an Electronic Double Slit Interference Experiment

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We present a controlled interference experiment of ballistic electrons in a two-dimensional electron gas. While the phase along one interfering path is kept constant, the phase along the second interfering path is varied using a biased metallic gate, thereby enabling a direct measurement of the phase accumulated underneath this gate. Surprisingly, in addition to the expected oscillatory signal measured as a function of the gate bias, we observe a longer period signal with approximately half the expected frequency.

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In recent years there have been many measurements in metallic and semiconductor structures sensitive to the phase of the electronic wave function. Examples include Aharonv-Bohm (AB) oscillations, weak localization, universal conductance fluctuations, and persistent currents (PC) [1]. In all these examples the accumulated electronic phase was changed using an externally applied magnetic field leading to a phase difference between interfering paths. In two of the examples (AB and PC), the measured currents are found to be essentially periodic in magnetic flux with a period of $\phi_0 = h/e$, where h is Planck's constant and e is the electronic charge. This periodicity as well as its higher harmonic $h/2e$ found in AB experiments performed with cylinders [2] and in PC measurements performed with an ensemble of isolated rings [3] can be very well explained in terms of the area defined by the interfering paths and the electronic charge. A different way for obtaining a phase change, which does not involve an external magnetic field, is by using a biased metallic gate. The voltage applied to the gate partly depletes the electrons underneath it, thereby reducing their velocity and leading to a slower accumulation of phase in the gated region.

In the present work we present a controlled experiment of interference between electronic paths, where the phase accumulated along one set of paths is kept constant while the phase accumulated along a second set of paths is modulated by a biased metallic gate. This procedure enables a direct measurement of the phase difference between the two sets of paths or the accumulated phase of the paths traversing underneath the modulating gate. Surprisingly, in addition to the expected oscillatory signal as a function of the gate voltage, we observe an additional period, similar in magnitude but with approximately *half* the expected frequency. We are presently unable to find any plausible mechanism that would produce such a low frequency. Phase modulation with a magnetic field revealed only the ordinary h/e AB-type oscillatory signal due to the magnetic flux contained between the two sets of paths.

Experiments were carried out on a variety of molecular beam epitaxy grown GaAs-AlGaAs heterojunctions supporting two-dimensional electron gas (2DEG) with carrier densities ranging from 2×10^{11} to 4.5×10^{11} cm^{-2} and low temperature electron mobilities higher than 10^6 cm^2/V s. All heterojunctions are uniformly doped in the AlGaAs with an overall distance between surface and 2DEG of some 70 nm. The laterally patterned structures (see Fig. 1) consist of two *point contacts,* formed by biased metallic gates, facing each other and separated by $L = 5$ μm; one is used as an injector (E) and the other as a collector (C). Halfway between the two point contacts (some 2.5 μm from E and C) a metallic gate consisting of two air bridges is deposited, forming, when negatively biased, two narrow slits (separated by 0.8 μm and <0.2 μm wide each). Near one of these slits a *phase modulating* gate (G), typically of length $d = 0.5$ μm, is placed and is used to vary the phase of the electronic paths traversing from E to C and through this slit. The 2DEG is contacted at various points in the injector and the collector regions as well as on both sides of the "double slit gate" (base region, B), using standard AuGeNi alloyed Ohmic contacts. All measurements were taken at 1.4 K using standard lock in techniques. A small ac voltage (smaller than the temperature) was applied across the injector point contact (V_{EB}). The open circuit C-B voltage V_{CB} indicative of the number of electrons passing through the two slits and reaching the collector (where the interference takes place), is then measured in a *four terminal configuration.*

Using the multiprobe Landauer formula, it can be shown that the measured collector voltage V_{CB} is directly proportional to the transmission probability to travel from the injector to the collector T_{CE} [4,5]. Theoretically, T_{CE} can be expressed as a coherent sum of two path amplitudes leading from E to C, $a(p_1)$ and $a(p_2)$, where p_1 denotes the paths passing through the first slit and underneath the modulating gate, and p_2 denotes the other interfering paths passing through the second slit. Applying a negative voltage V_G to the modulating gate

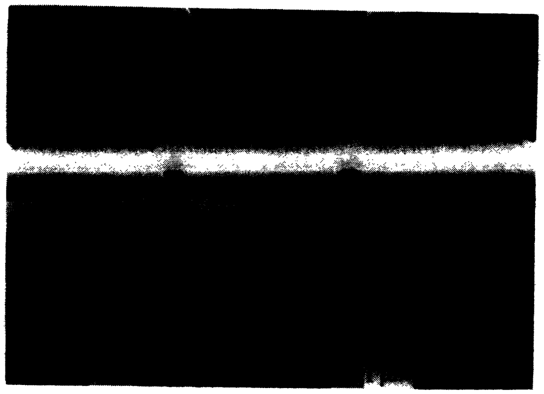

FIG. 1. A top view micrograph of one of the devices used in the experiment. The light areas are the metallic gates deposited on top of the GaAs-AlGaAs heterostructure.

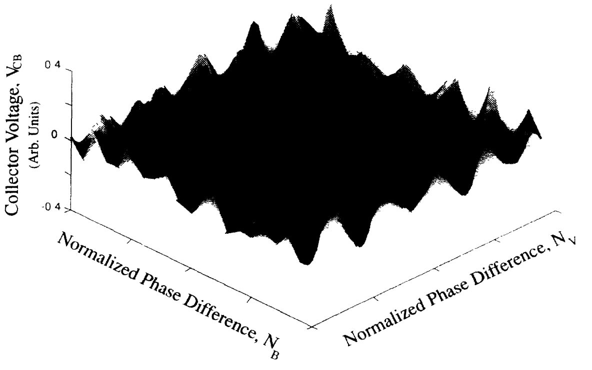

FIG. 2. The measured collector voltage (after subtracting a uniform background) vs both normalized phase difference, N_V and N_B. Note the equal phase lines corresponding to $N_V + N_B =$ const. In this device, the periodicity in magnetic field is 20 G.

results in a partial depletion of the 2DEG underneath this gate, and thus to a phase change $\Delta\varphi_V$ of the complex amplitude $a(p_1)$. The collector voltage V_{CB} is therefore expected to oscillate as a function of V_G with a period corresponding to one added wavelength to the paths p_1. It can be shown that by assuming a constant capacitance between the modulating gate and the 2DEG, the collector voltage is expected to be periodic in

$$N_V = \frac{\Delta\varphi_V}{2\pi} = \frac{k_F d}{2\pi}\left[1 - \sqrt{1 - \frac{V_G}{V_{\mathrm{dep}}}}\right],$$

where V_{dep} is the depletion voltage of the modulating gate [5]. Similarly, applying a magnetic field also causes a phase change in each of the amplitudes $a(p_i)$, equal to $\varphi_B(p_i) = \frac{e}{\hbar}\int_{p_i} \mathbf{A} \cdot d\mathbf{l}$, $\mathbf{A}$ being the vector potential produced by the external magnetic field, $\mathbf{l}$ is the coordinate variable along each path, and i represents the path. The overall phase difference between the two interfering amplitudes is given by $\Delta\varphi_B = (e/\hbar)\oint \mathbf{A} \cdot d\mathbf{l} = 2\pi\phi/\phi_0$, where ϕ is the flux enclosed by the two interfering sets of paths. Therefore, V_{CB} is expected to be periodic also in $N_B = \Delta\varphi_B/2\pi = \phi/\phi_0$, each period corresponding to the addition of one flux quanta ϕ_0 to the area enclosed by the two sets of paths.

After subtracting a uniform background signal, the measured collector voltage is plotted in Fig. 2 as a function of both normalized accumulated phases, N_V and N_B. The most pronounced feature seen in Fig. 2 is the equal phase lines corresponding to $N_V + N_B =$ const. A slice at a constant magnetic field (chosen arbitrarily) clearly exhibits in Fig. 3(a) two oscillatory signals, the expected one with a period $\Delta N_V = 1$ and an additional slower oscillatory signal marked by arrows. A Fourier transform of the signal, plotted as a function of the frequency (normalized to the expected frequency), is shown in Fig. 3(b). It reveals the two frequencies: The additional frequency being about *half* the expected one. The signal, however, measured as function of magnetic field (obtained from a slice through the surface at $V_G =$ const in Fig. 2) reveals only one period in N_B. The measured periodicity in magnetic field agrees within 15% with the expected one estimated by using the area enclosed by straight lines connecting the two point contacts through the two slits (these lines describe the two interfering sets of paths). This agreement is excellent considering the fact that the area we use is defined only by four points in the plane. The experiments were repeated on numerous samples fabricated

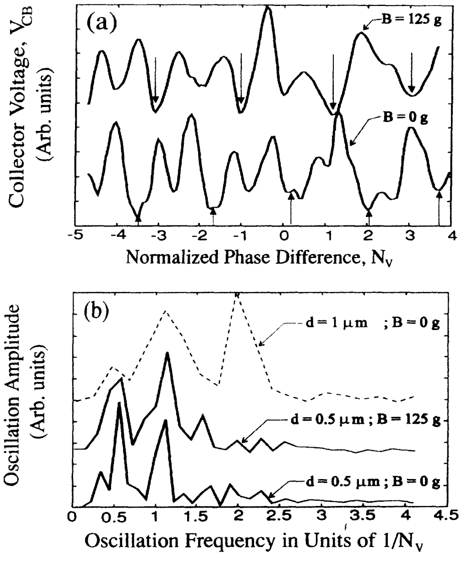

FIG. 3. (a) The measured collector voltage vs the normalized phase difference N_V for two different magnetic fields ($B = 0$ and 125 G). The modulation gate length $d = 0.5$ μm. The minimas of the lower frequency signal are marked by arrows. (b) Fourier transform of the measured collector voltage for two different gate lengths [the solid lines are a Fourier transform of the signals shown in (a)]. Two frequencies are clearly seen. The unexpected lower frequency signal is at approximately half the expected one. Note that both frequency signals are independent of magnetic field and scale with the gate length.

from the same heterostructure as well as on heterostructures with different electron densities. While the values of the two frequencies measured were found to depend only on gate length and carrier density (as expected), their relative amplitudes were found to vary nonsystematically from one device to another as well as after thermal cycling. This behavior is attributed to the specific impurity configuration being different in each device.

Because of technological difficulties in producing the double slit structure, we have also carried out experiments in configurations that do not contain the two slits [5,6] and found, once again, the unexpected lower frequency. In such a configuration we observe a larger interference signal that can be estimated also by two partial sums over paths: one sum pertaining to all paths passing underneath the modulating gate and the other containing all remaining paths. The most significant paths contributing to the oscillatory behavior of the collector voltage are those contained in a *diffraction limited* width of approximately $\sqrt{L\lambda}$ near the edge of the modulating gate, with λ being the electron's wavelength. In our structures, the diffraction limited width is only some 500 nm, hence, most quantum paths are passing in close proximity to the *edge* of the modulating gate, a region that could add, in principle, some unexpected effects. The appearance of both periods in the two configurations (with and without the slits) rules out any spurious effects due to the edge of the modulating gate.

We have also observed a similar lower frequency signal in an experiment specifically designed to detect transmission resonances through an electronic Fabry-Pérot resonator. In this experiment (done at 100 mK), electrons are injected (from a point contact) directly above a potential barrier formed by an electrostatic gate located 100 nm away from the injection point. As the applied voltage to the gate increases, transmission resonances (typically 1% in magnitude), corresponding to an addition of half an electronic wavelength along the barrier, are seen. However, again a lower frequency signal corresponding to approximately half the expected one is also observed. Similar transmission resonances should also be present, in principle, above the modulating gate in the interference experiments. However, due to the weaker signals measured in these experiments we are unable to resolve them even when the modulating gate is extended to cover both slits.

We have conducted a few obvious tests in an attempt to identify the origin of the unexpected periodicity. First, we changed the length of the modulating gate d. Figure 3(b) shows the Fourier transforms of data taken with two samples, with $d = 0.5$ and 1 μm. As seen, both frequencies, expected and unexpected, scale linearly with the length of the modulating gate, suggesting that the lower frequency originates also from a phase accumulated underneath the modulating gate. Another test measured the corresponding phase coherence length l_ϕ of the paths responsible for the longer period signal. This was done by measuring the temperature dependence of the amplitude of the interference signal (height or area of the Fourier peak) [6]. This amplitude is a measure of the number of electrons that traverse the distance L without undergoing any phase randomizing processes and is therefore proportional to e^{-L/l_ϕ}. By doing these measurements we obtain the temperature dependence of l_ϕ that corresponds to the lower frequency signal and find it to be similar to that of the higher frequency signal, as clearly seen in Fig. 4. This indicates that both periods are derived from similar paths and are *destroyed* in the same manner. Electron-electron (*e-e*) interactions, involving large energy exchange between the injected electrons and the Fermi sea electrons, were found to be responsible for the measured l_ϕ [5,6,7].

Although we are presently unable to explain the origin of the lower frequency signal, we are able to exclude a few possibilities.

(1) Geometrical effects.—To rule out geometrical effects, which might be intrinsic to our specific interference configuration, analogous, slitless, experiments were designed using light and water waves. In the light-wave experiment, the phase change along one group of paths was obtained by varying the width of a dielectric material (glass) inserted appropriately. In the water-wave experiment, the depth of the water bath was varied along a small distance for approximately half of the interfering paths. In both experiments we observed only the expected *high* frequency, suggesting that a pure wave phenomenon cannot explain the appearance of the lower frequency signal.

(2) A second electronic subband in the 2DEG.—The presence of an additional electronic subband can, in principle, provide an additional frequency signal in the gated experiments but still provide only a single frequency signal with magnetic flux. A change in the

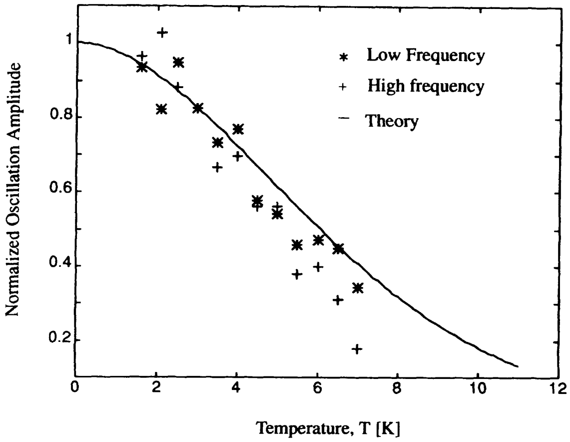

FIG. 4. Temperature dependence of the normalized oscillation amplitude of the two frequency signals. The solid line is the behavior expected, theoretically due to *e-e* scattering.

density, caused by the modulating gate, changes the Fermi wavelength of electrons in both subbands. In the simplest case, where electrons in the two subbands are of equal mass, a change in the Fermi level will cause a smaller change in the Fermi wavelength of the electrons in the lower subband, compared to that in the upper subband. Therefore, second subband electrons will produce a higher frequency interference signal. In order to obtain a signal with half the frequency one would require second subband electrons with mass smaller by approximately a factor of 4. Moreover, we did not find any experimental evidence for an additional subband. Utilizing Shubnikov–de Haas (SdH) measurements, where an additional subband should have been manifested via an additional periodicity in the magnetoresistance oscillations, we find only one type of carriers with density higher, by some 10%, from that extracted from Hall measurements. In addition, via magnetic focusing (MF) measurements [8], we did not observe any additional peaks that should have been indicative of a second subband [9]. Again, however, we find via MF measurements a local density higher by some 30% from that measured via Hall measurements. Finally, cyclotron resonance (CR) measurements did not detect second subband electrons either [10].

(3) Spin orbit (SO) interactions.—Moderately strong electric fields in bulk GaAs, resulting from the inherent lack of inversion symmetry and due to the potential confining the 2DEG, are responsible for SO interactions of the 2D electrons [11,12]. The SO interaction leads to two spin-related electronic subbands and can therefore explain, in principle, the appearance of two interference signals. However, the currently known value of the SO coupling constant in 2DEG in GaAs [13] is much too small to explain the strong effect we observe.

It is also known, both theoretically and experimentally, that strain can lead to an enhancement of SO interaction due to stronger electric fields in the deformed lattice [14]. There are two possible mechanisms that may cause strain in our samples: The first is due to different expansion coefficients of the metal gate and GaAs and is therefore important at low temperatures [15]. The second is due to the piezoelectric effect caused by the applied voltage to the modulating gate. Even though both effects are added to the commonly found SO interaction, they are insufficiently strong enough (with the currently available data) to cause a significant splitting of the subbands and thus explain the observed periodicity.

It is interesting to note that if we assume an *ad hoc,* large enough, SO coupling constant, which is necessary to explain the appearance of both frequencies, it would then be also possible to explain the different densities measured via Hall, SdH, and MF measurements discussed above. However, this is still in contradiction with the fact that an additional spin subband was not observed directly in SdH, MF, and CR experiments.

In summary, interference of ballistic electrons was studied in a double slit interference configuration, where the phase difference between the interfering amplitudes was obtained by a biased metallic gate. Apart from the expected periodicity as a function of the gate voltage, an additional lower frequency (approximately half the expected one) is observed. The two signals have comparable magnitudes, their frequency scale with the length of the modulating gate, and their amplitudes decay similarly as the temperature increases. We are currently unable to explain the origin of the lower frequency signal. The fact that the unexpected signal is so robust and its frequency is approximately half the expected one suggests that it may have a fundamental origin.

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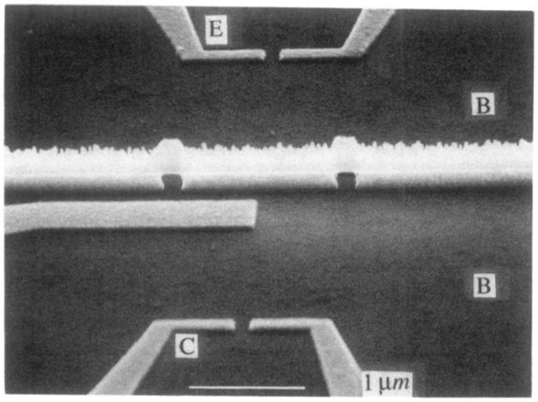

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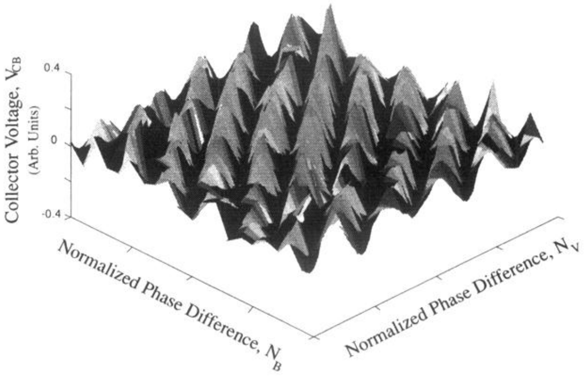

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