Novel Interference Effects between Parallel Quantum Wells

S. Datta, M. R. Melloch, S. Bandyopadhyay, and R. Noren
School of Electrical Engineering, Purdue University, West Lafayette, Indiana 47907

and

M. Vaziri, M. Miller, and R. Reifenberger
Department of Physics, Purdue University, West Lafayette, Indiana 47907
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This Letter describes a novel concept that can lead to new quantum interference effects with potential applications in switching devices. The interference occurs between currents flowing in two parallel channels formed by contiguous GaAs quantum wells. Preliminary experiments with a simple structure show oscillations in the conductance as a function of the magnetic field with a period close to h/e indicating an Aharonov-Bohm effect.

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Oscillatory magnetoresistance has been reported in bulk Mg[1] and in cylinders[2,3] and wire arrays[4] made of a number of different metals. The work on cylinders and wire arrays was stimulated by the prediction made by Al'tshuler, Aronov, and Spivak (AAS)[5] that the resistance of a metallic ring must oscillate as a function of the magnetic flux enclosed, with a period of $h/2e$ which is one-half that expected for the Aharonov-Bohm effect in vacuum.[6] Very recently, oscillatory magnetoresistance in submicron-diameter Au rings has been reported[7] with a period of h/e. This effect is different from the AAS effect and has been described earlier in several theoretical papers[8–10] where it was shown that a *one-dimensional* metallic ring should exhibit a large oscillatory magnetoresistance with a period of h/e even if there is frequent elastic scattering. The effects described in this paper are similar to this latter effect rather than the AAS effect.

The work on the Aharonov-Bohm effect in solids reported so far has concentrated on metals. It seems worthwhile to investigate these effects in semiconductor microstructures for several reasons. First, the development of sophisticated film growth techniques like metal-organic chemical-vapor deposition and molecular-beam epitaxy make it possible to fabricate ultrathin layered structures of high purity with atomically sharp interfaces. The transport channel can be isolated from the surface by a wide-gap semiconductor thus reducing surface effects. Very high mobilities ($\sim 10^6$ cm^2/V-sec) have been achieved in these structures and small structures with nearly "ballistic" transport between the contacts have also been reported.[11] Second, the carrier concentration can be varied over orders of magnitude by use of the gate electrode in a field-effect-transistor- (FET-) like structure. Third, the carrier concentration is typically orders of magnitude less than those in metals. This makes the de Broglie wavelength of electrons at the Fermi level much longer than in metals, so that even structures with dimensions ~ 0.1 μm can provide essentially single-mode propagation. It was pointed out in Ref. 8 that the quantum interface effects are reduced significantly (relative to the strictly one-dimensional case) if many transverse modes are present. Fourth, the possibility of controlling the interference phenomenon with a third electrode presents intriguing device possibilities.

Consider, for example, the hypothetical structure shown in Fig. 1(a). The conduction channels can be defined by a metallic gate electrode formed lithographically on the surface of an FET-like structure. Alternatively the conduction channels could be GaAs layers surrounded by AlGaAs. We are assuming that the

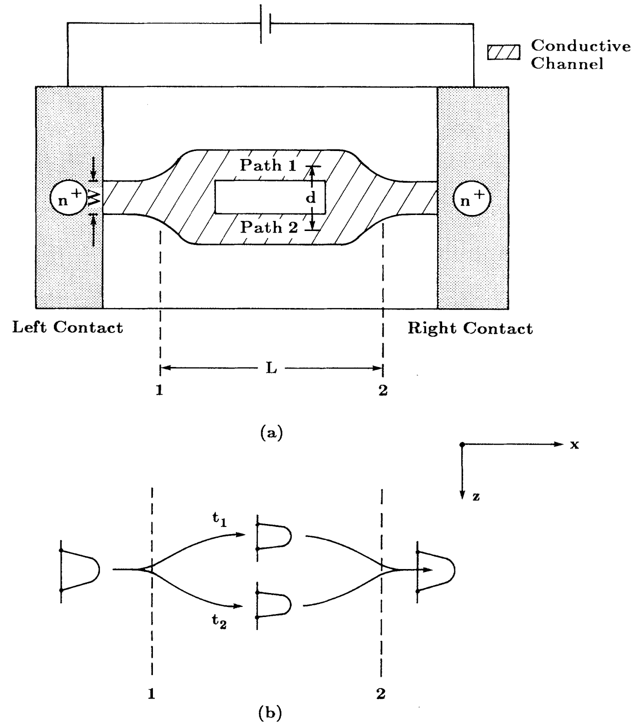

FIG. 1. A hypothetical structure that may exhibit large quantum interference effects. (a) Configuration. (b) Electron wave functions at various planes.

channels are narrow enough so that at low temperatures there is only one propagating transverse mode whose wave function is shown in Fig. 1(b). At a carrier density of $10^{10}/cm^2$ this is ensured if $W \sim 0.1$ μm. The conductance of the channel depends on the squared magnitude of the transmission coefficient T for an electron from plane 1 to plane 2. If t_1 and t_2 are the transmission coefficients through paths 1 and 2, respectively, then, neglecting multiple reflection effects, we have

$$|T|^2 = |t_1 + t_2|^2 = 2|t|^2(1+\cos\phi), \quad (1)$$

with the assumption that t_1 and t_2 are identical in magnitude with a phase difference of ϕ. We can then write the conductance G as

$$G = G_0(1 + \langle\cos\phi\rangle), \quad (2)$$

where the angle bracket denotes an average over the ensemble of electrons. Thus the conductance of the structure can be modulated by a change in the phase ϕ between the channels. This can be done either with a magnetic field B_y (Aharonov-Bohm effect),

$$\phi = eB_y Ld/\hbar, \quad (3)$$

or with a transverse electrostatic field $\mathscr{E}_z$ (electrostatic Aharonov-Bohm effect),[12]

$$\phi = e\mathscr{E}_z Ld/\hbar v_x, \quad (4)$$

where v_x is the velocity of the electron in the x direction. The possibility of modulating the current with a transverse electric field has potential applications in switching devices as a "quantum interference transistor" requiring extremely low drain and gate voltages. The dependence of the conductance G on ϕ is more complicated than given in Eq. (2) if multiple reflections are taken into account, but the essential features are the same. Scattering dilutes the effect by causing a spread in ϕ and can be reduced by making the length L short. Moreover, if the structure is "one dimensional" with only one propagating transverse mode, then large interference effects are possible despite frequent elastic scattering, as long as inelastic scattering is negligible.[8]

The structure in Fig. 1 is difficult to fabricate. The experimental results reported in this Letter were obtained by use of the structure shown in Fig. 2. At first sight, it appears that in this structure the electrons transmit from the contacts into the channels with arbitrary phase relationships, unlike the structure in Fig. 1, where the wave functions in the channels are always in phase. This would reduce the interference effect significantly, since the contacts play roles analogous to that of the "polarizer" and "analyzer" in optical interference experiments. However, even in this structure it might be possible for the electrons to transmit into the channels at least partially in phase from the contacts

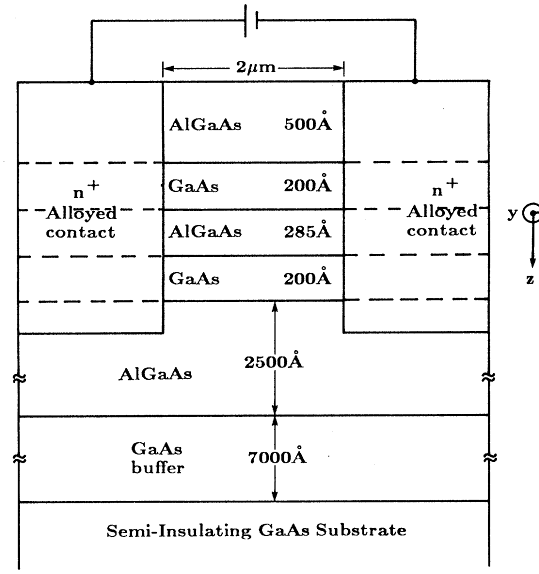

FIG. 2. The double quantum well structure used in the experiments (magnetic field along y axis).

for the following reason. The contacts are basically the same as the channels except that they are doped heavily n type by the Ge from the Au-Ge alloy.[13] The heavy doping leads to increased tunneling between the channels inside the contact regions making the lowest-energy state a symmetric combination of wave functions in the two channels. Of course, the precise nature of the Au-Ge alloyed contact is not known and it is difficult to predict the electronic wave functions in the contacts with any certainty. It is, however, possible to design alternative structures that deliberately enhance tunneling at the two ends by making the barrier layer thinner; such structures can be grown with present-day technology by etching and regrowth and should exhibit large Aharonov-Bohm effects. The n^+ regions are approximately 2 μm apart and are delineated by photolithography. The thickness of the structure in the y direction was ion milled to approximately 2 μm. The structure is thus multimoded in the y direction. Although the channels are undoped, they are fairly conductive, possibly because of carriers induced by surface or interface charges. The carrier density in the channels estimated from conductance measurements is $\sim 10^{11}/cm^2$. We can view this structure as two FET-like channels in parallel. The electron transport is probably partially ballistic. The transit time of the electrons from one contact to the other is estimated to be ~ 10 ps; this is comparable to the elastic scattering time which is estimated to be ~ 3 ps from typical values of mobility. Inelastic scattering times around 50 ps have been reported at 1 K in GaAs quantum wells with similar carrier concentrations.[14]

The sample was mounted on a probe that rested in the magnetic field of a superconducting solenoid ($B<5$ T). The magnetic field, directed along the y axis, was varied by a microcomputer, while the current through the sample, at a fixed voltage of 260 μV, was recorded on a chart recorder. Figure 3(a) shows the variation in the sample conductance as a function of the magnetic field at 4.2 K. There is a monotonic decrease in the conductance up to a magnetic field of 0.5 T. Superimposed on this monotonic decrease is a regular periodic oscillation in the conductance that gradually dies out. Figure 3(b) shows the conductance with the smooth monotonic component suppressed. The oscillations are now clearly evident with a period of $B_0=480$ G. The theoretical period for Aharonov-Bohm oscillations is given by

$$B_0 = h/eA,$$

where A is the area enclosed by the two paths. The center-to-center distance between the channels is 485 Å giving $A = 2\ \mu\text{m}\times 485$ Å, so that

$$B_0 = 430 \text{ G}.$$

This is about 10% less than the experimental value, which is possibly because in-diffusion of the contacts makes the length of the channels less than 2 μm. Note that the theoretical period of AAS oscillations would have been one-half the above value (~ 215 G). The magnitude of the oscillations $\Delta\sigma/\sigma$ is approximately 0.08%. Oscillatory magnetoresistance in single quantum wells has been reported when the diameter of the cyclotron orbits becomes comparable to the well width; but this requires much larger magnetic fields for our structure and is therefore not relevant to our experiment.[15]

The experiment was repeated with a second sample. It showed no change in the conductance at 4.2 K with

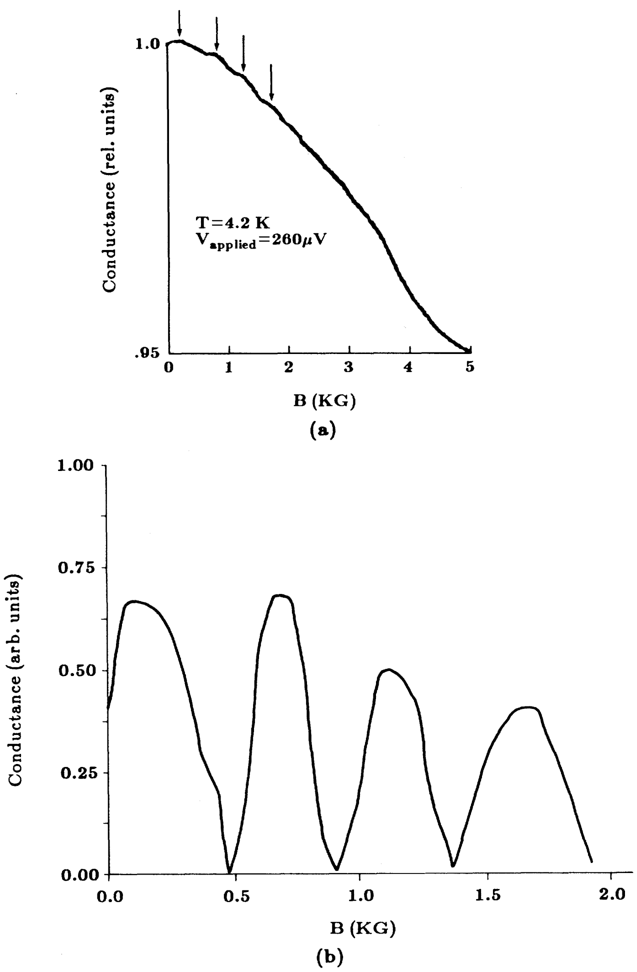

FIG. 3. Conductance σ vs magnetic field B_y at 4.2 K for sample 1. (a) Experimental data with peaks indicated by arrows. (b) Experimental data with monotonic component suppressed.

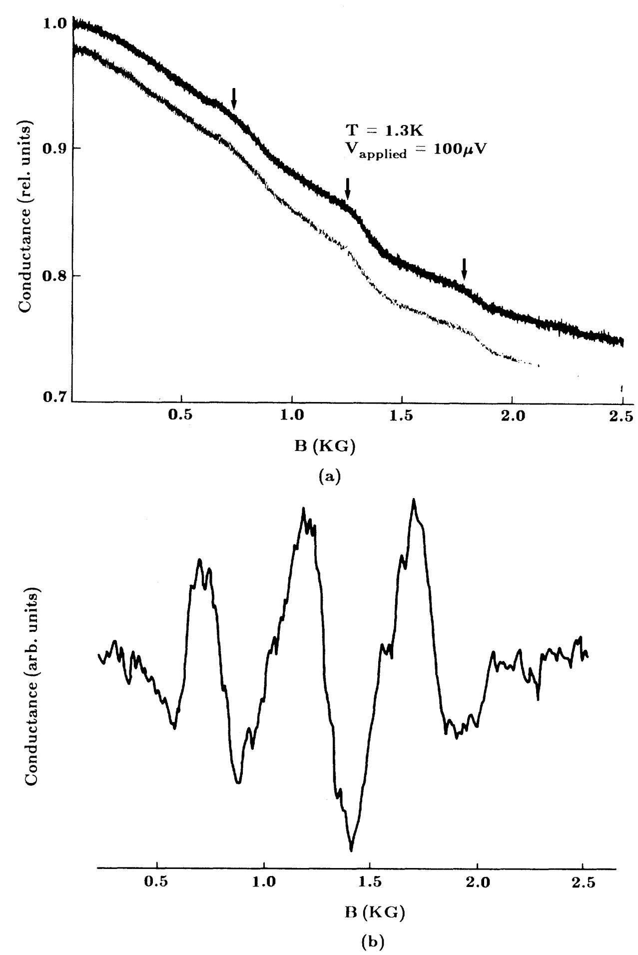

FIG. 4. Conductance σ vs magnetic field B_y at 1.3 K for sample 2. (a) Experimental data with peak indicated by arrows (the lower trace is taken with the current reversed). (b) Experimental data with monotonic component suppressed.

magnetic field. However, when the temperature was reduced to 1.3 K, oscillations in the conductance as well as the monotonic decrease were observed (Fig. 4). The magnitude of the oscillations $\Delta\sigma/\sigma$ is approximately 0.5%. The magnetoresistance is unchanged when either the current or the magnetic field is reversed.

This monotonic decrease in the conductance by ~ 30% is observed consistently at 1.3 K in every sample we have tested, although the magnitude of the oscillatory component varies widely from sample to sample. In some samples the oscillations are very small (~ 0.05% or less), but the large positive magnetoresistance is still present. It is difficult to explain this magnetoresistance in conventional terms. Past experiments with long single-channel GaAs-$Al_xGa_{1-x}As$ heterostructures[14] have shown negative magnetoresistances at temperatures below 1 K, but no positive magnetoresistance was reported with magnetic fields up to 5 T parallel to the layers. In our samples, too, we do not observe either the positive magnetoresistance (monotonic component) or the oscillatory magnetoresistance when one of the channels is etched away. This is different from the magnetoresistance reported in earlier experiments on the AAS effect[1-4] which is present even for single wires and is well understood.

In summary, this Letter describes a novel concept that can lead to a new class of quantum interference effects with potential applications in switching devices. This is a new type of interference involving electron transport *parallel* to the heterolayers rather than *perpendicular* to them as in resonant tunneling devices.[16] Preliminary experiments with a simple structure show an oscillatory magnetoresistance with a period that agrees closely with that expected for the Aharonov-Bohm effect. Further experiments are under way to study the effects of various parameters such as channel length, carrier concentration, and transverse electric field (z directed) on the observed effects.

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[1]N. B. Sandesara and R. W. Stark, Phys. Lett. **53**, 1681 (1984).

[2]D. Yu. Sharvin and Yu. V. Sharvin, Pis'ma Zh. Eksp. Teor. Fiz. **34**, 285 (1981) [JETP Lett. **34**, 272 (1981)]; B. L. Al'tshuler, A. G. Aronov, B. Z. Spivak, D. Yu. Sharvin, and Yu. V. Sharvin, Pis'ma Zh. Eksp. Teor. Fiz. **35**, 476 (1982) [JETP Lett. **35**, 588 (1982)].

[3]M. Gijs, C. Van Haesendonek, and Y. Bruynseralde, Phys. Rev. Lett. **52**, 2069 (1984).

[4]B. Pannetier, J. Chaussy, R. Rammal, and P. Gandit, Phys. Rev. Lett. **53**, 718 (1984); D. J. Bishop, J. C. Liciui, and G. J. Dolan, Appl. Phys. Lett. **46**, 1000 (1985).

[5]B. L. Al'tshuler, A. G. Aronov, and B. Z. Spivak, Pis'ma Zh. Eksp. Teor. Fiz. **33**, 101 (1981) [JETP Lett. **33**, 94 (1981)].

[6]Y. Aharonov and D. Bohm, Phys. Rev. **115**, 485 (1959); R. G. Chambers, Phys. Rev. Lett. **5**, 3 (1960).

[7]R. A. Webb, S. Washburn, C. P. Umbach, and R. B. Laibowitz, Phys. Rev. Lett. **54**, 2696 (1985).

[8]Y. Gefen, Y. Imry, and M. Y. Azbel, Phys. Rev. Lett. **52**, 129 (1984).

[9]M. Büttiker, Y. Imry, and M. Y. Azbel, Phys. Rev. A **30**, 1982 (1984).

[10]M. Büttiker, Y. Imry, R. Landauer, and S. Pinhas, Phys. Rev. B **31**, 6207 (1985).

[11]M. S. Shur and L. F. Eastman, Solid-State Electron. **24**, 11 (1981).

[12]Giorgio Matteucci and Giulio Pozzi, Phys. Rev. Lett. **54**, 2469 (1985).

[13]A. Piotrowska, A. Guivarch, and G. Pelons, Solid-State Electron. **26**, 179 (1983).

[14]B. J. F. Lin, M. A. Paalanen, A. C. Gossard, and D. C. Tsui, Phys. Rev. B **29**, 927 (1984).

[15]J. Yoshino, H. Sakaki, and T. Hota, Surf. Sci. **142**, 326 (1984).

[16]L. Esaki and R. Tsu, IBM J. Res. Dev. **14**, 61 (1970); R. Tsu and L. Esaki, Appl. Phys. Lett. **22**, 562 (1973); L. L. Chang, L. Esaki, and R. Tsu, Appl. Phys. Lett. **24**, 593 (1974).