Aperiodic Magnetoresistance Oscillations in Narrow Inversion Layers in Si

J. C. Licini[(a)] and D. J. Bishop
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

and

M. A. Kastner[(a)] and J. Melngailis
Research Laboratory for Electonics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 24 June 1985)

Aperiodic oscillations are observed in the magnetoresistance of narrow inversion layers in *p*-type Si. The dependence of the oscillations on Fermi energy indicates that they are not the result of a shift with magnetic field of the energies of electronic states but rather arise from a change in the phase of the wave functions.

PACS numbers: 73.40.Qv, 71.55.Jv, 72.15.Gd

Aperiodic oscillations have been observed in the magnetoresistance of small-cross-section Au, AuPd, and GaAs wires.[1,2] We report here the observation of such oscillations in narrow Si inversion layers. The ability to vary the Fermi energy (chemical potential) in this system has made it possible to show that the oscillations are not the result of a shift with magnetic field of the energies of electronic states (Dingle[3]), but rather arise from a change in the phase of the wave functions.

The devices used for the present studies are metal-oxide-Si field-effect transistors (MOSFET's) in which the metal gate electrode is a narrow ($\sim 70\times 50$ nm) tungsten wire. The wire is created by glancing-angle evaporation of the W into a 50-nm step etched in the 100-nm oxide on the Si(100) surface.[4] A positive voltage, V_G, applied to the gate electrode creates an *n*-type inversion layer at the surface of the *p*-type Si and simultaneously confines the inversion layer to a narrow strip under the wire running in the (110) direction. Except for the replacement of Al by W in the gate wire, which results in better wire uniformity, the structures used here are identical to those used in previous measurements[5] of the large nonmonotonic variations of the conductance as a function of V_G near threshold. The measurements reported here, however, were made at V_G well above threshold in order to explore a more weakly localized regime (where the conductance variations with v_G are only a few percent). In the effort to improve yield, wire uniformity, and consistency of electronic properties, fabrication modifications to change gate material and device encapsulation unintentionally resulted in lower mobility (~ 2000 cm^2/V-s at 4 K) and wider channels (~ 270 nm) than obtained for previous devices.

Magnetoresistance measurements at widely spaced gate voltages are shown in Fig. 1. The negative magnetoresistance at fields below 1 kOe is well described by the theory of weak localization.[6] The surprising new behavior observed is the aperiodic oscillation of the resistance as a function of magnetic field perpendicular to the silicon surface. The oscillations are symmetric (see Fig. 1) under reversal of field direction (unlike those in Au and AuPd wires), persist unattenuated to the largest fields applied (25 kOe), and are reproducible for fixed V_G and for small excursions of V_G. When V_G is changed by large amounts, as shown in Fig. 1, the amplitude (about 1% of the channel resistance) and typical period (about 1 kOe) remain about the same for gate voltages ranging from 0.8 to 4.8 V above threshold, corresponding to carrier densities from 3.6×10^{11} cm^{-2} to 2.2×10^{12} cm^{-2} and channel resistances from 300 to 50 kΩ. The samples were mounted in a ^{3}He-^{4}He dilution refrigerator which can reach 50 mK. The ac voltage used to measure sample resistance was always less than kT/e to eliminate elec-

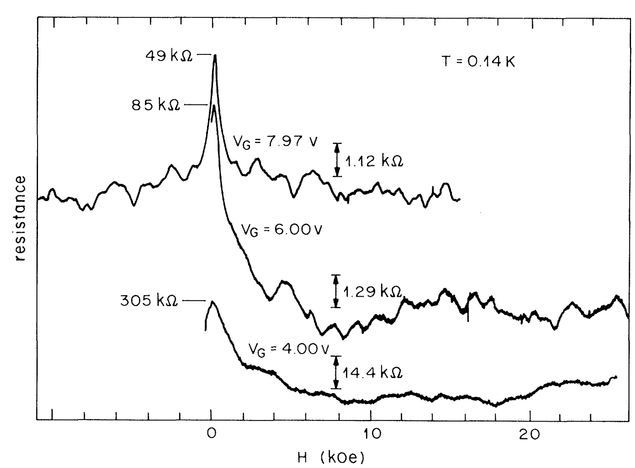

FIG. 1. Change of resistance with magnetic field at four gate voltages V_G (threshold at $V_G \simeq 3.4$ V). Note that the resistance scales are different at each V_G.

tron heating and other nonlinearities.[5]

A question raised by the data of Fig. 1 is whether the oscillations are the result of an energy shift of the electronic eigenstates or, instead, are caused by a change in the phase of the wave functions. The first of these effects would result if, for example, structure in the density of states were moved past the Fermi energy, E_F, by the magnetic field. For Shubnikov–de Haas oscillations, this structure is caused by the magnetic field[7]; the case in which the structure is caused by the small size of the sample is discussed by Dingle.[3] To explore this possibility, we measured the dependence of the resistance and the magnetoresistance on gate voltage in more detail.

In Fig. 2 is a plot of resistance as a function of v_G at zero magnetic field. On this expanded scale, oscillations are observed which are comparable in size ($\sim 1\%$) to those in the magnetoresistance. Such features have been ascribed by Wheeler, Choi, and Wisnieff[8] and Skocpol *et al.*[9] to one-dimensional subband structure in the density of states which modifies the weak localization and interaction effects. The spacing of this structure in gate voltage, 100–200 mV, corresponds to a change of E_F by $\Delta E_F \simeq 0.3$–0.6 meV. To explore whether field-induced energy shifts of the density of states could be the origin of the structure in the magnetoresistance, we measured the magnetoresistance at closely spaced values of V_G near 8 V. The results are shown in Fig. 3. If the effect of the magentic field were to shift the energies of states relative to E_F, continuously with V_G, then, in a corresponding way, small changes in V_G should cause the structure in the magnetoresistance to shift in field, at least for such small variations of V_G as used in Fig. 3. On the contrary, for small δV_G, the oscillations retain their phase from one V_G to another, while for larger δV_G, the phase becomes uncorrelated. One cannot observe any consistent pattern of gradual shifts of the oscillations with V_G. This provides strong evidence that the magnetoresistance oscillations do not result from energy shifts of the eigenstates.

Instead, they must result from field-induced changes in the phase of the electronic wave functions, resulting in modulation of the current. One way in which such modulation might arise is if there were, in the channel, closed-loop conduction paths. These would give rise to quantum interference or "Bohm-Aharonov" effects which cause the overall resistance of the loop to be a periodic function of the magnetic flux enclosed. Such an effect with period $hc/2e$ was predicted by Al'tshuler, Aronov, and Spivak[10] and observed by Sharvin and Sharvin.[11] A second effect with period hc/e has been predicted by several groups[12] and observed by Webb *et al.*[13]

The closed-loop paths required for the Bohm-Aharonov explanation could only arise from macroscopic heterogeneities (MH) in the inversion layer. Such heterogeneities might be caused by long-range potential fluctuations resulting in multiply connected preferred conduction paths. Two observations favor such a MH model. First, as seen in Fig. 1, the typical period of the oscillations is ~ 1 kOe, corresponding to a flux quantum penetrating an area $hc/2eH \sim (W/2)^2$, where W is the width of the channel, which is reasonable. Second, the temperature depen-

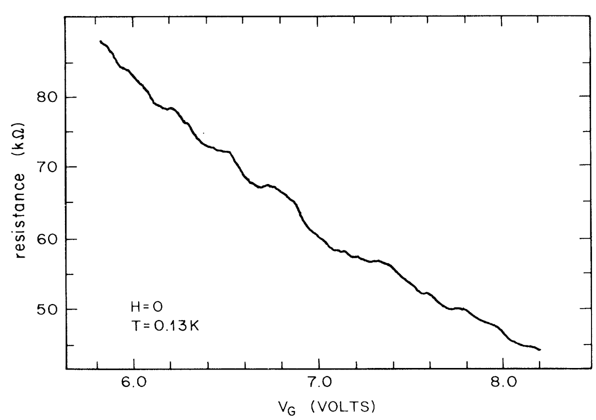

FIG. 2. Resistance vs V_G at $H=0$. The overall decrease of R with V_G results from the increase of electron density.

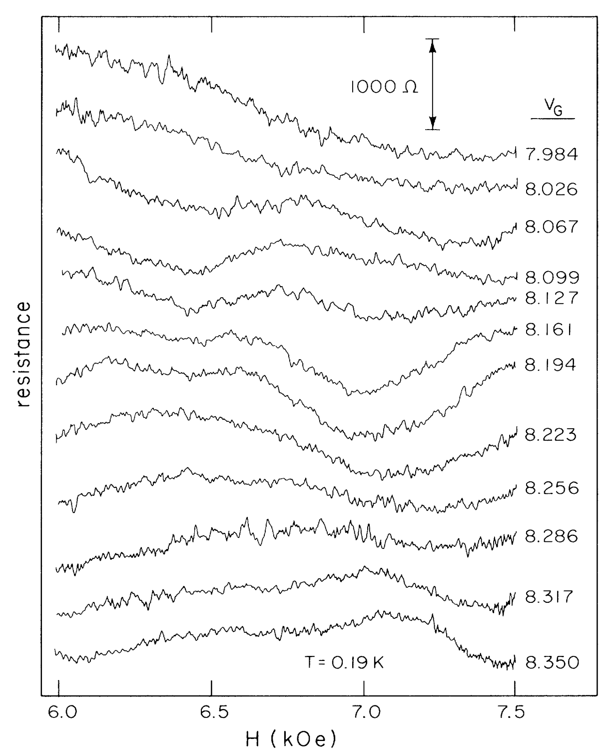

FIG. 3. Magnetoresistance at closely spaced values of V_G. Channel resistance ~ 50 kΩ.

dence of the oscillations is strong when the inelastic diffusion (Thouless) length $L_T \sim W$, as expected[10] for Bohm-Aharonov oscillations for a path of this size. Figure 4 shows the temperature dependence of the amplitude (peak-to-valley) of two, arbitrarily chosen oscillations like those in Fig. 3. This temperature dependence is consistent with $\exp(-L_0/L_T)$, where L_0 is some fixed length, and L_T is known[14] to vary as $T^{-1/2}$. As discussed below, $L_T \sim 120$ nm at 2.2 K, which therefore gives $L_0 \sim 3W$.

However, several pieces of evidence argue against the MH model. The oscillations are qualitatively independent of V_G. When V_G is increased, the Fermi energy is raised and the conducting paths should widen. This would result in an increase in the typical period, which is not observed. Furthermore, because the sample is much longer than it is wide, it is likely that there are many closed-loop paths in the channel, if there are any at all. The model, therefore, suggests a high degree of heterogeneity which is inconsistent with our low-field magnetoresistance results, as we now show.

As already mentioned, the field dependence below ~ 1 kOe is consistent with the predictions of the weak localization theory. We find that at 2.2 K the magnetoresistance is well described by the 2D form[15] with $L_T = 120$ nm. Measurements of the conductance versus V_G for a wide MOSFET prepared simultaneously with the narrow ones gives a narrow-device width of 270 nm, with the assumption of the same mobility for both size MOSFET's. At and below 1.5 K there are clear deviations from the 2D form characteristic of 1D

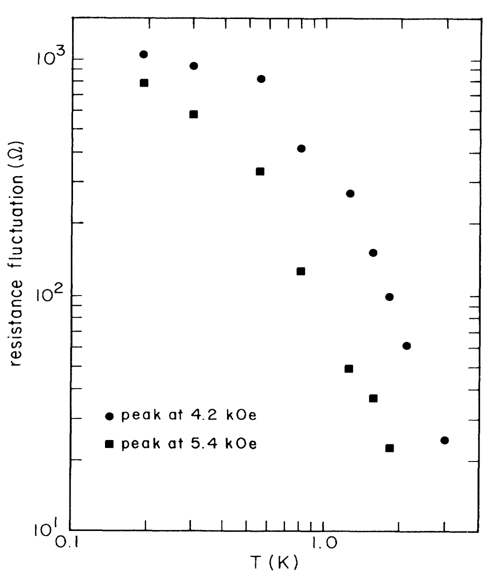

FIG. 4. Peak-to-valley amplitude of two resistance oscillations as a function of T.

behavior. However, since L_T decreases with T only as $T^{-1/2}$, even at 0.5 K, $L_T \leq W$. Thus the system is not truly one dimensional for any of the measurements reported here, but not truly two dimensional at the lowest temperatures.

The agreement between localization theory and our low-field magnetoresistance strongly suggests that our devices are highly disordered but homogeneous conductors. This is true for the Au and Au-Pd wires as well, so that the ubiquity of the magnetoresistance oscillations also suggests that they do not result from macroscopic heterogeneities. Furthermore, observation of oscillations in the MOSFET's as well as in the wires, despite their differences in conductance by a factor $\sim 10^4$, points to a more universal origin.

An explanation which would account for this universality has recently emerged from the simulations of Stone[16] and the analytic calculations of Lee and Stone.[17] Stone's calculations revealed aperiodic magnetoresistance oscillations of disordered conductors in the metallic regime which were a result of quantum interference and were, therefore, independent of material properties. Lee and Stone[17] have recently argued that all metallic samples, independent of size, will have conductance fluctuations with magnetic field or chemical potential which are of order $e^2/\hbar\pi^2$ at sufficiently low temperature. Both the simulations and analytic work pertain to samples smaller in size than the inelastic diffusion (Thouless) length. In that case the resistance is directly related to the transmission and reflection coefficients for incident plane-wave electronic states. As a result, the resistance depends on the phase of the wave functions in the disordered region, which, in turn, varies with magnetic flux through that region and with chemical potential (Fermi energy).

Most of the arguments against the MH model favor the model of Lee and Stone, because it requires no heterogeneity. Furthermore, they predict that there will be an energy scale, which we call the eigenfunction-correlation energy E_ϕ, defined in a way such that for changes in Fermi energy $\Delta E_F < E_\phi$ the magnetoresistance oscillations will have a correlated phase. The data of Fig. 3 show that for our devices E_ϕ corresponds to ΔV_G of 20–80 mV or $E_\phi \approx 0.06$–0.23 meV. This should be equivalently measurable from the oscillations in Fig. 2, and these do have a period of about the same order: $\Delta V_G \sim 100$–200 mV, consistent with a common origin. Lee and Stone have not yet calculated the temperature dependence of the oscillations in the limit that L_T is short compared with the sample dimensions. For our devices, the sample length L is ~ 30 times L_T at 0.5 K. One expects the oscillations to be reduced by at least a factor $(LW)^{1/2}/L_T$ from incoherent summation of the number of blocks of area L_T^2 in the sample. Multiplying the low-T magnitude of the oscillations ΔG

$\simeq 5\times 10^{-7}\ \Omega^{-1}$, from Fig. 4, by this factor gives a value about 10 times smaller than $e^2/\hbar\pi^2$. Although the agreement with the prediction of Lee and Stone is suggestive, a definitive comparison must await a proper treatment of the temperature dependence.

We have observed noiselike, but reproducible, magnetoresistance oscillations in a narrow, but still two-dimensional, Si inversion layer. The ability to vary the Fermi energy has allowed us to show that the oscillations are not the result of field-induced shifts of structure in the density of states but rather arise from changes in the phase of the eigenfunctions. This capability made it possible, furthermore, to show that the changes of E_F necessary to change the phase of the oscillations is about the same as that to observe oscillations in the zero-field conductance itself. While Bohm-Aharonov oscillations resulting from macroscopic heterogeneities cannot be ruled out, the bulk of the evidence points to a more universal explanation like that of Lee and Stone, in which the oscillations are a direct consequence of quantum interference in the disordered conductor.

We acknowledge useful discussions with P. A. Lee, A. D. Stone, H. I. Smith, A. E. White, R. C. Dynes, G. E. Blonder, and G. J. Dolan. We thank R. W. Mountain and colleagues at Lincoln Laboratories for performing initial fabrication steps, and J. M. Carter and other members of the Submicron Structures Laboratory at Massachusetts Institute of Technology for their assistance. This work was supported, in part, by the Joint Services Electronics Program under Contract No. DAAG-29-83-K003.

[a]Also at the Department of Physics, Massachusetts Institute of Technology, Cambridge, Mass. 02139.

[1]C. P. Umbach, S. Washburn, R. B. Laibowitz, and R. A. Webb, in *Proceedings of the Seventeenth International Conference on Low Temperature Physics, LT-17, Part II—Contributed Papers,* edited by U. Eckern, A. Schmid, W. Weber, and H. Wühl (Elsevier, New York, 1984), pp. 717–718, and Phys. Rev. B **30**, 4048 (1984).

[2]G. E. Blonder, A. E. White, and R. C. Dynes, to be published.

[3]R. Dingle, Proc. Roy. Soc. London, Ser. A **212**, 47 (1952).

[4]D. C. Flanders and A. E. White, J. Vac. Sci. Technol. **19**, 892 (1981).

[5]R. F. Kwasnick, M. A. Kastner, J. Melngailis, and P. A. Lee, Phys. Rev. Lett. **52**, 224 (1984).

[6]G. Bergman, Phys. Rep. **107**, 1 (1984).

[7]A. B. Fowler, F. F. Fang, W. E. Howard, and P. J. Stiles, Phys. Rev. Lett. **16**, 901 (1966).

[8]R. G. Wheeler, K. K. Choi, and R. Wisnieff, Surf. Sci. **142**, 19 (1984).

[9]W. J. Skocpol, L. D. Jackel, R. E. Howard, H. G. Craighead, L. A. Fetter, P. M. Mankiewich, P. Grabbe, and D. M. Tennant, Surf. Sci. **142**, 14 (1984).

[10]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)].

[11]D. Yu. Sharvin and Yu. V. Sharvin, Pis'ma Zh. Eksp. Teor. Fiz. **34**, 285 (1981) [JETP Lett. **34**, 272 (1981)].

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

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

[14]D. J. Bishop, D. C. Tsui, and R. C. Dynes, Phys. Rev. Lett. **44**, 1153 (1980).

[15]D. J. Bishop, R. C. Dynes, and D. C. Tsui, Phys. Rev. B **26**, 773 (1982).

[16]A. D. Stone, Phys. Rev. Lett. **54**, 2692 (1985).

[17]P. A. Lee and A. D. Stone, Phys. Rev. Lett. **55**, 1622 (1985).