Manipulating the transmission of a two-dimensional electron gas via spatially varying magnetic fields

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We explore how the transmission properties of a two-dimensional electron gas can be modified by manipulating the fringing magnetic fields that emanate from a set of patterned gates, deposited on the top surface of its heterojunction. We propose a multigate device whose conductance is shown to depend sensitively upon the relative magnetization of its gates, and which may therefore be of use as a planar magnetoresistance device, or as a memory structure. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1861957]

The integration of semiconductor devices with nanomagnetic elements offers the possibility to realize new generations of electronic devices, in which the fringing fields generated by these elements are exploited to manipulate current flow at the nanoscale. There has been much interest, for example, in the development of hybrid Hall devices, in which a nanomagnet is deposited on the top surface of a submicron-sized semiconductor junction.[1–7] Small variations of an external magnetic field modify the field pattern emanating from this magnet, giving rise to a detectable change in the junction resistance that may be utilized as the basis of a magnetic-field sensor. Another possible application is in spintronics, where various proposals for spin filters have been made in which magnetic elements are incorporated into semiconductor nanostructures to generate spin-dependent transmission of electrons.[8–11]

We explore here how the transmission properties of a two-dimensional electron gas (2DEG) can be modified by manipulating the fringing magnetic fields, which emanate from a set of patterned gates deposited on the top surface of its heterojunction. While there have been many studies of electron transport, both in the presence of a spatially varying magnetic field,[12–22] and in magnetic superlattices,[23–27] we demonstrate how large changes in the resistance of such a structure can be generated by using an external magnetic field to switch the relative magnetic orientation of neighboring gates. We believe that such a system could therefore be useful as a magnetoresistance device, offering the benefits of both its *planar* structure, and its compatibility with existing semiconductor-processing techniques.

The system that we study is shown in Fig. 1, and consists of a high-mobility 2DEG that is located a distance z_o below the surface of a heterojunction. (For the purpose of implementation, we will assume here the case of a GaAs/AlGaAs heterojunction, for which the electron effective mass $m^* = 0.067\ m_o$.) Two pairs of closely spaced magnetic gates are deposited on the top surface of the heterojunction, and the terminology that we use to denote the critical dimensions (t, d, d_c, and d_L) of these gates is also indicated in Fig. 1. The gates are aligned along the y direction, and each generates a normal magnetic-field component in the 2DEG plane, whose magnitude varies strongly along the x direction. The precise form of this spatially varying magnetic field depends on the specific orientation of the gate magnetization,[13] and in our discussion, we consider the case wherein the field distributions emanating from the different magnets overlap strongly with each other. We focus, as well on the situation in which the magnetization of each gate is aligned either parallel, or antiparallel, to the $+x$ direction, and envisage the switching between these two configurations as being achieved by the application of a small external magnetic field.

For a *single* gate, whose magnetization points along the $+x$ direction, the variation of the normal magnetic-field com-

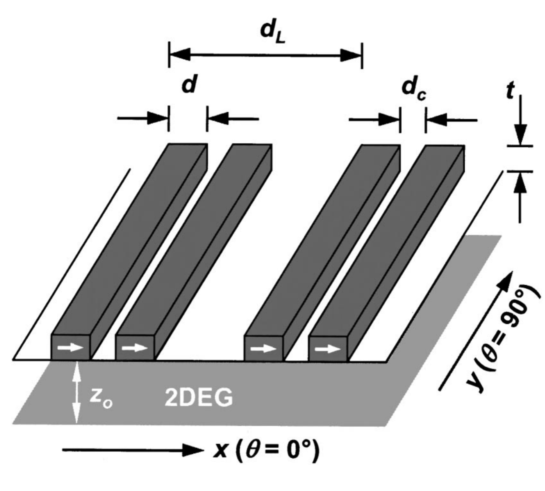

FIG. 1. Schematic of the system that we study here. The device consists of two pairs of closely spaced gates, deposited on the top surface of a high-mobility heterojunction.

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ponent, as a function of position in the 2DEG plane, is given by[13]

$$B(x) = B_o\left[K\left(x + \frac{d}{2}\right) - K\left(x - \frac{d}{2}\right)\right], \quad B_o = \frac{M_o t}{d},$$
$$K(x) = \frac{z_o d}{(x^2 + z_o^2)}. \tag{1}$$

A similar equation is obtained when the magnetization points along the $-x$ direction, although its sign is now *opposite* at all points to that described by Eq. (1). In the discussion that follows, we make use of the following parameters when discussing the effects of this magnetic field: the cyclotron frequency $\omega_c \equiv eB_o/m^*$; the magnetic length $l_B \equiv (\hbar/eB_o)^{0.5}$; and the cyclotron energy $E_o \equiv \hbar\omega_c$. For a realistic comparison with experiment,[3–5,21–27] we assume $B_o = 0.1$ T in our calculations, yielding $E_o = 0.17$ meV and $l_B = 81$ nm.

To solve for electron transmission in a spatially varying magnetic field such as that of Eq. (1), we make use of the time-independent Schrödinger equation

$$\left[\frac{p_x^2}{2m^*} + \frac{[p_y + eA_y(x)]^2}{2m^*}\right]\psi(x,y) = E\psi(x,y), \tag{2}$$

where p_x and p_y are the momentum components of the electron in the 2DEG. (We do not include a spin-related term here, since we generally will be dealing with weak magnetic fields, for which spin degeneracy should not be lifted.) The magnetic vector potential arising from the magnetic field of Eq. (1) is given by[20]

$$A_y(x) = B_o d\left[\tan^{-1}\left(\frac{x + d/2}{z_0}\right) - \tan^{-1}\left(\frac{x - d/2}{z_0}\right)\right]. \tag{3}$$

For the multigate structure that we consider here, this analysis is easily extended by summing the vector potentials arising from the different gates. We then solve Eq. (2) numerically, making use of the results of transmission-matrix theory.[28] The important point here is that our analysis allows us to compute the transmission probability $T(E,\theta)$, of an electron with total energy E that is incident at an angle θ with respect to the $+x$ direction. The total transmission probability is then given by integrating over all possible angles between $+\pi/2$ and $-\pi/2$, and can be used to obtain the conductance of the device by making use of the Landauer formula. For this problem, the Landauer formula can be expressed as[19]

$$G(E) = G_0\int_{-\pi/2}^{+\pi/2} T(E,\theta)\cos\theta\, d\theta, \quad G_o = \frac{2m^* e^2 v_F L_y}{h^2}. \tag{4}$$

In this expression, L_y is the length of the magnetic gates along the y direction. It is worth noting that, in a typical implementation (we will consider a GaAs/AlGaAs heterojunction with $m^* = 0.067m_o$, $v_F \sim 10^5$ m s^{-1}, and $L_y \sim 10^{-4}$ m, $G_o \sim 10^3\, e^2/h$. We also point out that Eq. (4) is, of course, derived assuming ballistic transport in the 2DEG. In ultrahigh-mobility semiconductor material, the mean free path for transport can be of order several tens of microns at low temperatures,[29] while the gate separation should be of order a few hundred nanometers (see subsequent discussion). In integrating over all angles in Eq. (4), the assumption of ballistic transport may therefore be reasonable.

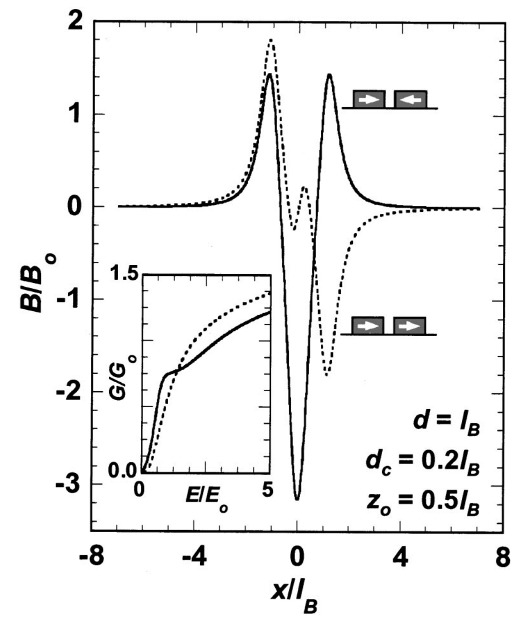

FIG. 2. Main panel: the variation of the normal magnetic-field component, generated in the 2DEG by a single pair of closely spaced gates, with the two magnetization configurations shown in the figure. Inset: calculated variation of the conductance with energy, for the two field distributions shown in the main panel. The solid and dotted lines correspond to the field distributions in the main panel.

To generate large changes in the conductance of the 2DEG, in the presence of a small applied magnetic field, the gates should be closely spaced to each other, to ensure strong overlap of their fringing fields. This point is illustrated in the inset to Fig. 2, in which we show the field distributions arising from a closely spaced pair of gates, when their magnetizations are aligned parallel and antiparallel to each other. These curves were obtained by using Eq. (1) to compute the superposition of the separate field distributions, generated by the two gates, and in these and all subsequent calculations, we assume $d = l_B$, $d_c = 0.2l_B$, $d_L = 6l_B$, and $z_o = 0.5l_B$. It is clear from Fig. 2 that reversing the relative orientation of the gate magnetization produces a significant change in the fringing fields that emanate into the 2DEG. In the inset to Fig. 2, we show how this change in magnetization is manifest in the conductance of the 2DEG, which we calculate by application of Eq. (4). Unfortunately, we see that the relative change in conductance between the two orientations is relatively small, and the two conductance curves even cross as the energy is varied.

For a more pronounced conductance modulation, we propose the structure shown in Fig. 1, which consists of two pairs of closely spaced gates. In Fig. 3, we show the magnetic-field distributions obtained for this structure, for several different magnetization configurations (indicated). Figure 4 shows the corresponding variation of the conductance with energy, computed using Eq. (4), for these configurations. In contrast to the behavior in the inset to Fig. 2, these curves show *resonances* at low energy, and *oscillatory* structure at higher energies. Such behavior is characteristic of resonant tunneling, and indicates that electrons are effectively confined between the two pairs of gates at low energies. We also note that the transmission is significantly suppressed when the gates in each pair are magnetized in parallel with respect to each other, but when the two sets of

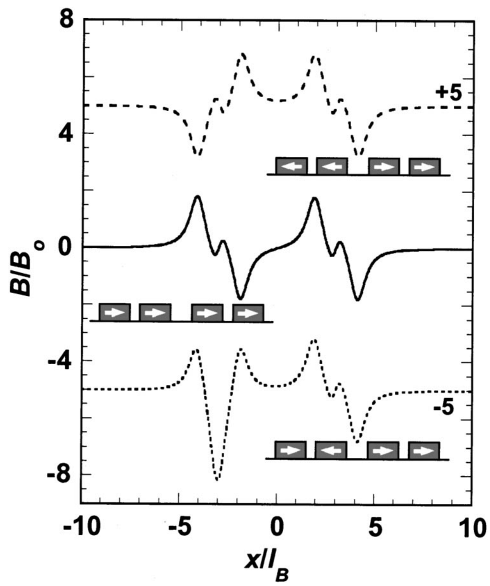

FIG. 3. The variation of the normal magnetic-field component, generated in the 2DEG by the device of Fig. 1, for the magnetization configurations shown in the figure.

gates are oppositely magnetized (dashed line in Fig. 4). Referring to the magnetic-field profiles in Fig. 3, we see that the field distribution in this case corresponds to a quantum-dot-like form, in which electrons move in a region of zero magnetic field near $x=0$ that is bound on either side by a high magnetic barrier.

The behavior shown in Fig. 4 suggests the possibility of realizing a magnetoresistive sensor that registers small changes in magnetic field as a significant change in the conductance of the 2DEG. Another possible use is as a memory structure, in which the conductance of the 2DEG could be used to provide readout of the magnetization history of the surface gates. In a practical implementation, one pair of gates could be formed from a magnetically hard material, while the other could be realized using a much softer material. The magnetization of the softer pair of gates could then be easily switched backward and forwards by a small external magnetic field, applied within the plane of the 2DEG, or by driving a current pulse through a control wire in close proximity to these gates (much as is done in conventional magnetic random access memory structures.)

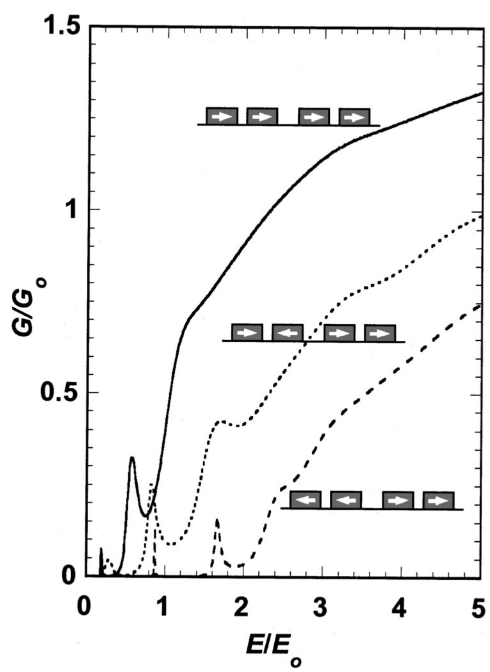

FIG. 4. The calculated variation of the conductance with energy for the device of Fig. 1. The solid, dotted, and dashed lines correspond to the different field distributions in Fig. 3.

In conclusion, we have explored how the transmission properties of a 2DEG can be modified by manipulating the fringing magnetic fields that emanate from a set of patterned gates, deposited on the top surface of its heterojunction. We have proposed a multigate device whose conductance has been shown to depend sensitively upon the relative magnetization of its gates, and which may therefore be of use as a planar magnetoresistance device, or as a memory structure.

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