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D. Lidsky; T. Hutchins-Delgado; P. Sharma; V. Dobrosavljevic; T. M. Lu

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D. Lidsky,[1,2,3,a)] T. Hutchins-Delgado,[1,2,3] P. Sharma,[1] V. Dobrosavljevic,[4] and T. M. Lu[1,2,a)]

AFFILIATIONS

[1]Sandia National Laboratories, Albuquerque, New Mexico 87185, USA
[2]Center for Integrated Nanotechnologies, Sandia National Laboratories, Albuquerque, New Mexico 87123, USA
[3]University of New Mexico, Albuquerque, New Mexico 87106, USA
[4]Department of Physics, Florida State University, Tallahassee, Florida 32306, USA

[a)]**Authors to whom correspondence should be addressed:** david.physicist1@gmail.com and tlu@sandia.gov

ABSTRACT

An increasing magnetic field perpendicular to an undoped semiconductor surface at low temperature is known to strengthen the binding of localized electrons to stationary ions, as the wavefunction's tails evolve from exponential to Gaussian. It is also known that application of a high bias voltage to a depleted semiconductor can liberate bound charge and induce a large drop in electrical resistance. We connect these established results to experimental electrical transport measurements on off-state germanium Schottky-barrier metal–oxide–semiconductor field-effect transistor (MOSFETs) with an aluminum oxide insulating dielectric and platinum germanide contacts. We make measurements at the three distinct orientations of the magnetic field with respect to the substrate and the current. At 6 K, we observe sharp attenuation of current by more than 2 orders of magnitude, within 60 mT, at a crossover magnetic field perpendicular to the substrate. A 1 T magnetic field attenuates the current by more than 4 orders of magnitude. The strength of the attenuation and the value of the crossover field are controlled by both the gate–source and drain–source voltages. The attenuation is much weaker when the magnetic field is parallel to the current. Finally, we orient the magnetic field parallel to the substrate, but perpendicular to the current, allowing us to distinguish charge hopping at the oxide interface from charge hopping in the bulk. This large off-state magnetoresistance can be exploited for cryogenic magnetic- and photo-detection, and for high-bias, low-leakage MOSFETs.

In an off-state p-type metal–oxide–semiconductor field-effect transistor (MOSFET), with no extended Bloch states, the drain–source current, I_{DS}, due to an applied drain–source voltage, V_{DS}, is from hole hopping between localized traps, often concentrated at the semiconductor–oxide interface. A magnetic field perpendicular to the plane of the substrate increases the binding energy of the carriers in their traps. Jouault showed that the carrier binding energy of magnetodonor in GaAs approximately doubles from 0 T to 10 T.[1] An increasing perpendicular magnetic field causes the holes to be more tightly bound, and the variational wave function shifts from exponential tails to Gaussian tails. This reduces the overlap between neighboring trap sites and suppresses I_{DS}. More detail is given in the supplementary material. Sladek has described theoretically how a magnetic field can increase the donor ionization energy and reduce the wavefunction overlap between donor sites, with experimental confirmation in n-doped indium antimonide (nInSb) at low temperature.[2] Others have noted a similar cause for large magnetoresistance in doped silicon covered with a thin native oxide, ascribing the non-linear current–voltage characteristics to impact ionization, abetted by the presence of a Schottky barrier and thin oxide dielectric. The high electric field at the barrier imparts more kinetic energy to the carriers that get across, increasing the probability of impact ionization. Experimentally, the magnetoresistance in Si–SiO_2–Al structures is stronger when there is an oxide tunneling barrier or a Schottky barrier, than when there are low resistance contacts. A kinetic model, in which the impact ionization coefficient decreases exponentially with the binding energy, agrees qualitatively with the data.[3,4]

The magnetic field can delay the onset of avalanche breakdown in Schottky diodes.[5] The suppression is more effective when the field is perpendicular to the plane of the substrate than when it is parallel.[6] In Mn/SiO_2/p-Si, the dc and ac resistance changes by 10^6 with a 200 mT change in magnetic field.[7] A number of authors have investigated magnetoresistance in germanium (Ge).[8–13] He investigated an Ag–pGe–Ag two-terminal device at temperatures from 300 K down to 77 K, with a sourced current as the independent variable, and found a negative differential resistance at high currents.[14] An increasing magnetic field shifted the onset of negative magnetoresistance to higher currents. Similarly, Chen reports that the increasing magnetic field pushes the breakdown voltage to higher values, for In–Ge–In.[15] Most of these studies treat two-terminal devices, meaning that while more than two contacts may be used for 4-point or Hall diagnostic measurements, the device has one independent electrical source connected across two terminals. In this work, we extend these previous works to a three-terminal device: a Ge MOSFET. The presence of the additional electrical contact, the gate, allows us to turn the magnetoresistance on and off.

We will show that at a high enough V_{DS}, denoted "V_{cross}," I_{DS} increases abruptly, by orders of magnitude. This is associated with a discontinuous change in voltage across the reverse-biased Schottky barrier, but not the forward-biased Schottky barrier, as seen by 4-point measurements. The discontinuous jump in current may be indicative of impact ionization. As the magnetic field increases, V_{cross} increases, because it takes more energy to liberate the electron from its B-field deepened trap. There are no discontinuous jumps in the on-state, because the conduction is by delocalized carriers, rather than by hopping. When the B-field is in-plane and perpendicular to the current, the impact ionization occurs only when the holes are deflected into the oxide, lending evidence to the theory that we have hopping between defects at the oxide interface. When the B-field is in-plane and parallel to the current, there is no abrupt jump in current. The small but finite magnetoresistance in this geometry may be due partially to perpendicular components of the B-field due to sample misalignment.

The device was fabricated by standard photolithography. Electrical contacts were formed by depositing platinum on the nominally undoped germanium substrate and thermally annealing to form platinum germanide. The insulating gate oxide layer is aluminum oxide.[16] A color-coded cross-sectional illustration of the Hall bar used in our transport experiments is shown in Fig. 1(a), and an optical microscope image is shown in Fig. 1(b). The channel is 800 μm long and 40 μm wide. A schematic cross section of the layers is shown in Fig. 1(c). To perform electrical characterization, the device is wire bonded to a printed circuit board and measured in a variable-temperature system with a base temperature of 6 K. DC gate–source and drain–source voltages are supplied by Keithley 2400 source-measure units. The magnetic field, B, is swept in a cycle, starting and ending at 0 Tesla (T). Explicitly, we sweep B from 0 to -1 T, then -1 to 1 T, and finally 1 to 0 T. The device characteristics, in the absence of magnetic field, were reported earlier.[16] The threshold gate voltage is -1.6 V. As the gate voltage gets more negative, the drain–source current increases, indicative of a pMOSFET.

The temperature dependence of the drain–source current, I_{DS}, is shown in Fig. 2. With no magnetic field, during cooling, the current increases from 16 μA at 300 K to 186 μA at 40 K, due to reduced phonon scattering. Below 40 K, the current starts decreasing due to free carrier freeze out, dropping to 3 nA at 6 K. At this temperature and small drain–source bias, the conduction is by variable range hopping. A magnetic field perpendicular to the substrate is more effective at suppressing current than a magnetic field parallel to the substrate and current.

The orientation of the current and the magnetic field with reference to the device, when the field is perpendicular to the substrate, is

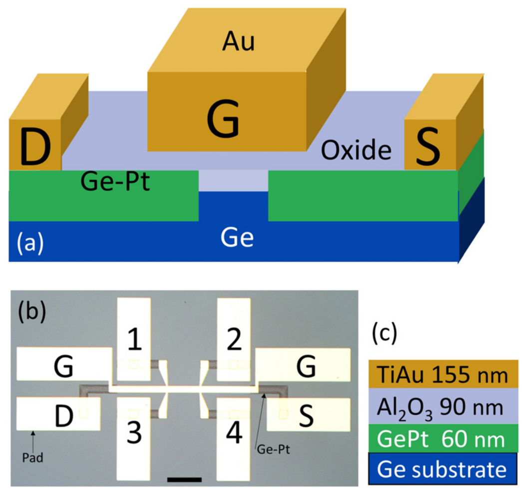

FIG. 1. (a) Sample cross section, with labeled drain (D), gate (G), and source (S). (b) Optical microscope image of the transistor, identifying the gate, source, drain, and Hall contacts 1–4. Black scale bar is 200 μm. All pads except for the gate electrically contact Ge–Pt, which lies on top of the germanium substrate. Hidden in this top view, the gate and Ge–Pt are electrically isolated by the aluminum oxide layer, as sketched in cross section in (a). (c) Cross-sectional schematic with layer thicknesses from top metal down to the substrate, not to scale.

shown in Fig. 3(a). In Fig. 3(b), the p-type transistor is on, with the gate voltage, V_{GS}, set to -10 V. For drain voltage magnitudes less than 0.5 V, the magnetoresistance is slight. It becomes noticeable at 0.6 V. At $V_{DS} = -1.4$ V, the current attenuates by a factor of 400 as B is swept from 0 T to -1 T. Near -0.75 T, there is a jump by a factor of 10. The attenuation probably continues beyond $|B| = 1$ T, but higher fields were not explored in this study. In Fig. 3(c), the p-type transistor is off, with the gate voltage, V_{GS}, set to $+10$ V. For $|V_{DS}| < 1$ V, the current attenuates smoothly with increasing magnitude of magnetic field. For $|V_{DS}| \geq 1$ V, there is an abrupt jump at a crossover value of the magnetic field, B_{cross}. For $V_{DS} = -1.8$ V and $V_{GS} = +10$ V [Fig. 3(c)],

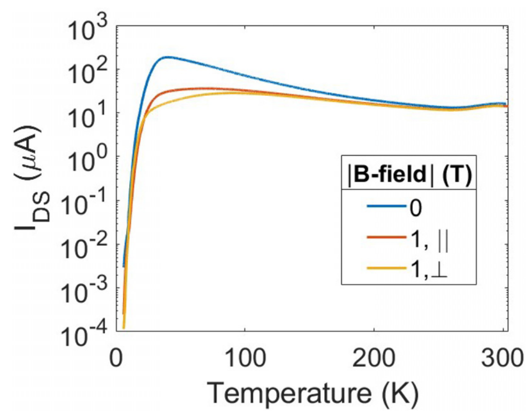

FIG. 2. Current vs temperature for no magnetic field, 1 T magnetic field parallel to current and substrate, and 1 T magnetic field perpendicular to current and substrate. Gate–source voltage is 0, and drain–source voltage is -50 mV. At 6 K, the current is 25 times lower with a 1 T perpendicular field than with no magnetic field.

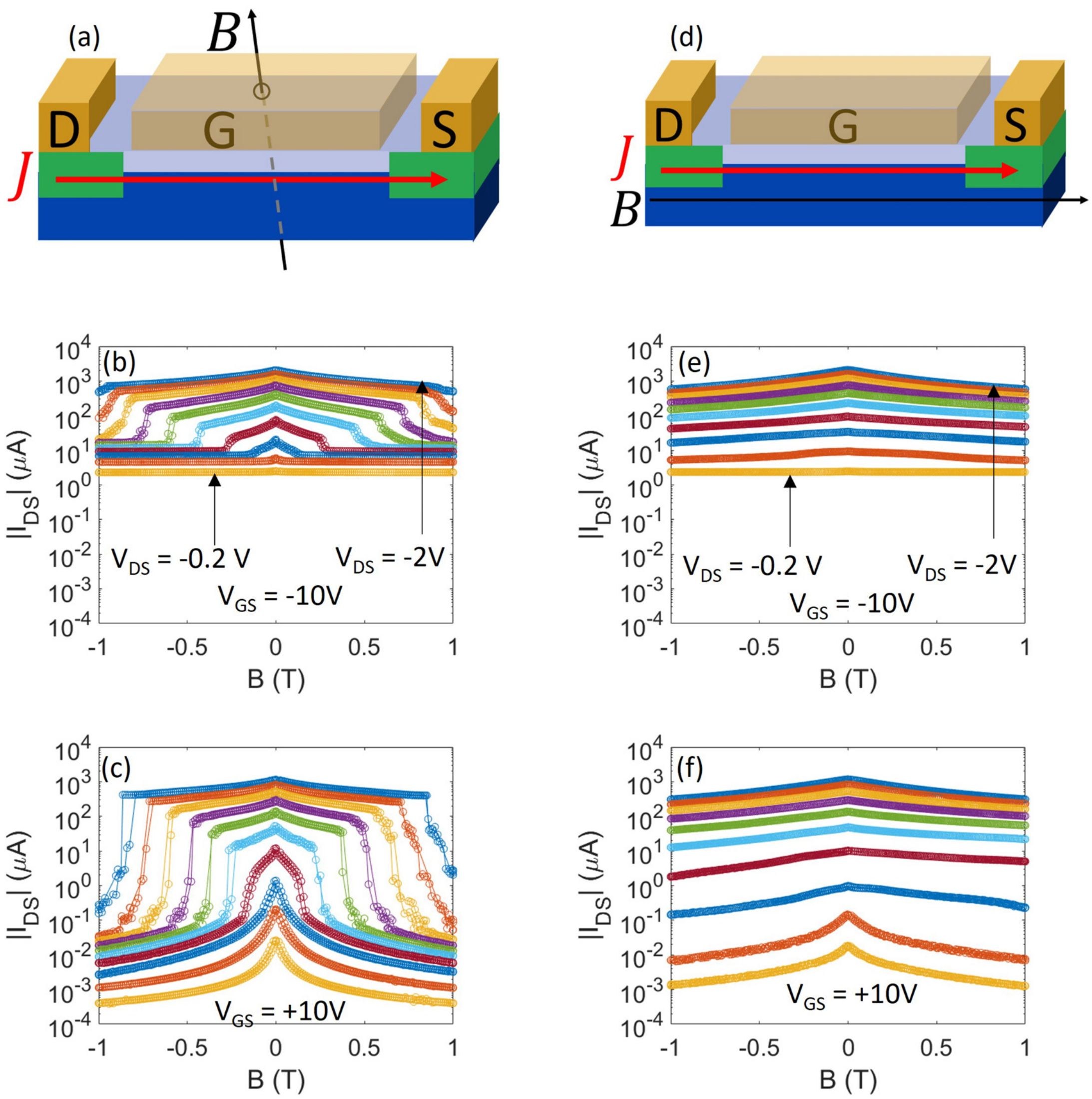

FIG. 3. Current vs magnetic field. Gate voltage is held constant in each figure. Drain voltage is stepped from −0.2 V to −2 V, in increments of −0.2 V. (a)–(c) B-field is perpendicular to substrate and to current. (d)–(f) B-field is parallel to current.

$B_{cross} \approx -0.75$ T. Here, the current attenuates by a factor of 600 within a 60 mT change in magnetic field. Between 0 and −1 T, the current attenuates by a factor of 23 000. The striking contrast between magnetoresistance in the on-state vs the off-state is due to the difference in the conduction mechanism. In the on-state, there is a two-dimensional hole gas (2DHG), with delocalized Bloch wavefunctions. In the off-state, there is variable range hopping between impurities, defects, and/or interface traps. The estimated trap density is $7.0 \times 10^{12}/\text{cm}^2$ V.[16] The hopping matrix elements vary strongly with magnetic fields less than 1 T, while the metallic conduction in the on-state varies weakly. The noticeable on-state magnetoresistance at high drain–source bias proves that there is a contribution to conduction from hopping, in both the on-state and the off-state. At low drain–drain source bias, hopping conduction is noticeable only in the off-state. Figures 3(d)–3(f) have the same set of gate voltages as (a)–(c), but now the magnetic field is parallel to the current, and the attenuation is more modest. Classically, a static magnetic field parallel to the velocity of a charged particle has no effect. Zawadzki's quantum theoretical calculation shows that a magnetic field does localize the charge in the direction parallel to the field, although not as severely as the localization in the plane perpendicular to the field.[17] This is consistent with Fig. 3, in which the magnetic field suppresses current more effectively when it is perpendicular to the plane of transport.

Figure 4(a) shows the response of the current to the drain voltage, with the magnetic field set to −0.3 T. Near $V_{DS} = 1.08$ V, the current jumps more than 100-fold within a voltage change of 2 mV. For this fixed magnetic field, we designate this value of V_{DS} as the crossover

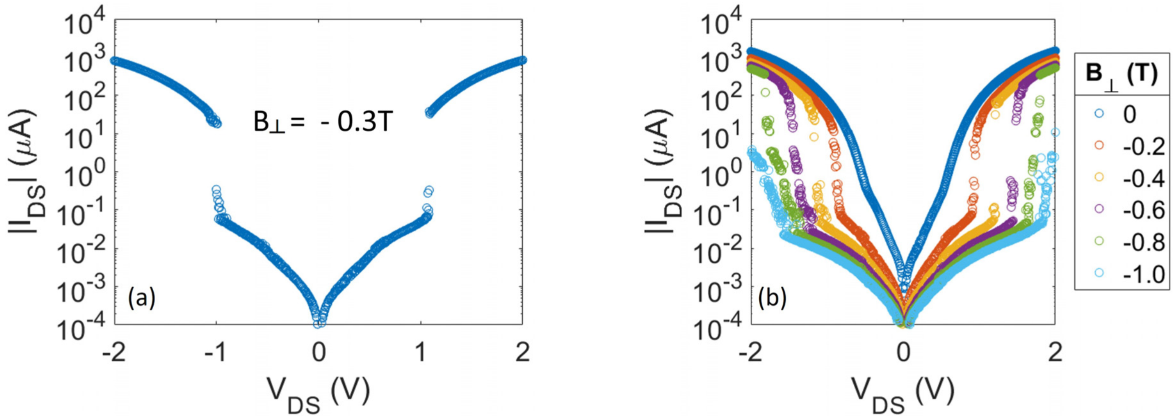

FIG. 4. (a) Discontinuous jump in current as a function of drain voltage, with perpendicular magnetic field fixed at -0.3 T. (b) Succession of curves like the one in (a), for discrete values of magnetic field.

voltage, $V_{cross} = 1.08$ V. The curve is broadly symmetric with respect to the sign of B. The deviations from perfect symmetry near $\pm V_{cross}$ are due to finite sampling of a continuously swept magnetic field, and also to the chaotic nature of the crossover to impact ionization and avalanche breakdown. The series of curves in Fig. 4(b) demonstrate that $|V_{cross}|$ increases with $|B|$. A higher voltage is required for impact ionization when the binding of the hopping charge to its impurity/defect site strengthens.

To identify the region where the impact ionization starts, we measure the voltage drops across individual segments along the Hall bar: V_{S2}, V_{21}, and V_{1D} [Figs. 1(b) and 5(c)]. In Figs. 5(a) and 5(d), we show the three voltage drops along the channel as a function of B, at $V_{GS} = +10$ V. At the relatively small $|V_{DS}|$ of 0.3 V, there is no crossover. However, in Fig. 5(d), at large $|V_{DS}| = 1.8$ V, there is a crossover at $B_{cross} \approx -0.78$ T. Significantly, the jump in current [Fig. 5(e)] coincides with a jump in voltage across the reverse-biased Schottky

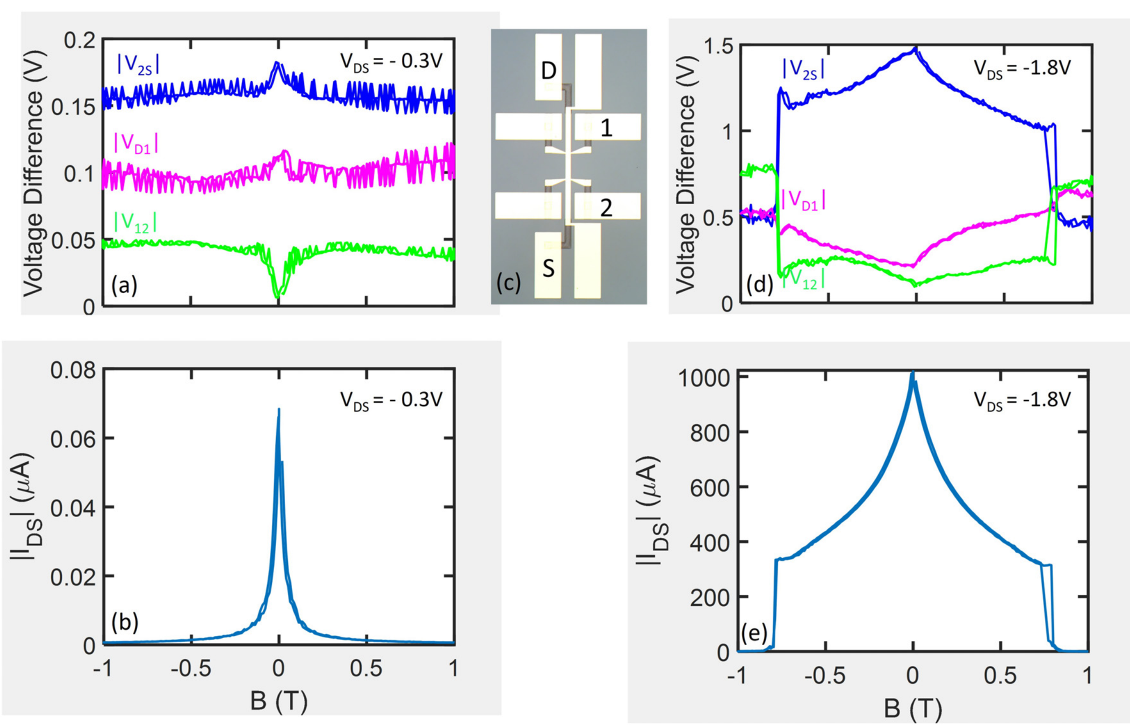

FIG. 5. Four-wire measurements across three separate segments. $V_{GS} = +10$ V and B-field is perpendicular to the substrate. (a) and (b) $V_{DS} = -0.3$ V. (d) and (e) $V_{DS} = -1.8$ V. (c) IDs of four contacts that determine the three voltage drops.

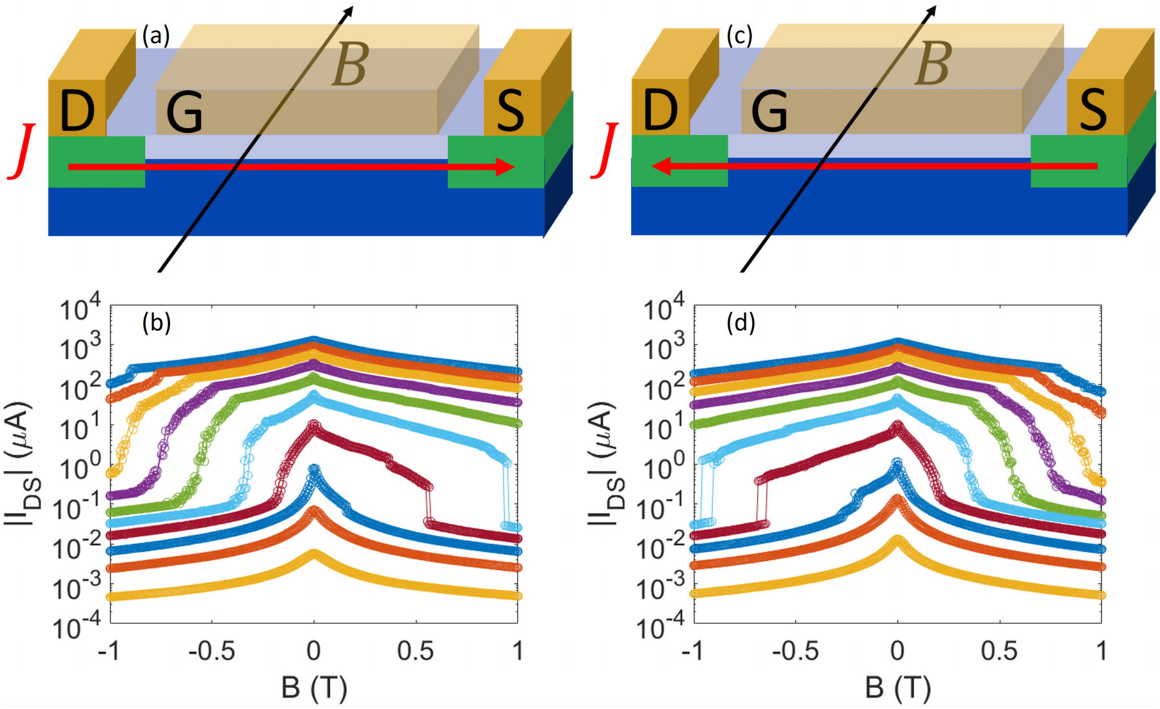

FIG. 6. Current vs magnetic field. Gate voltage is +10 V. Magnetic field is parallel to substrate and perpendicular to current, so that charges are deflected perpendicular to substrate. (a) and (b) Drain voltage is stepped from +0.2 V to +2 V, in increments of +0.2 V, so that positive B deflects holes *into the oxide*. (c) and (d) Drain voltage is stepped from −0.2 V to −2 V, in increments of −0.2 V, opposite in sign to (a), so that positive B deflects holes *into the Ge substrate.*

junction, V_{S2}, but not the forward-biased Schottky junction. At $B = -1\,T < -|B_{cross}|$, the holes are tightly bound to their centers of attraction, and the current I_{DS} is small. As B becomes less negative, the binding weakens, until impact ionization suddenly occurs at $B_{cross} = -0.78\,T$. When the magnetic field is just slightly more positive than $-0.78\,T$, the current increases sharply, and the voltage drop across the channel is reduced. That means that the resistance in the channel, which has no Schottky contacts, decreases. The major resistance is at the reverse-biased Schottky barrier near the source. This can be seen as $|V_{2S}|$ jumping from 0.5 to 1.25 V. As B increases from just above $-|B_{cross}|$ to 0, the current roughly doubles. It falls in a symmetric fashion as B is increased to just below $|B_{cross}|$, and then drops sharply as $|B_{cross}|$ is passed.

In Fig. 6, in the off-state, the magnetic field is oriented parallel to the substrate, but perpendicular to the current. Unlike the other two orientations shown in Fig. 3, now the sign of the magnetic field matters. In Figs. 6(a) and 6(b), the holes are deflected toward the oxide for positive B. At intermediate values of V_{DS}, one sees abrupt jumps in current near the crossover field, indicating avalanche from impact ionization at the oxide interface. However, for negative B, the magnetoresistance is a much smoother function of B. In this case, the holes are deflected into the bulk Ge substrate. This implies less impact ionization of trap states when the current travels through bulk Ge than when it travels along the oxide interface. When the sign of the drain–source voltages is reversed, as in Figs. 6(c) and 6(d), the curves are (qualitatively) reflected about the horizontal B-axis. This is consistent with the hypothesis of greater impact ionization in the oxide than in the bulk Ge, because now a positive B-field deflects carriers into the bulk and a negative B-field deflects carriers into the oxide. The density of traps, impurities, and defects is higher at the oxide interface than in the bulk Ge. Similarly, the density of hopping sites is higher near the interface. This is why for intermediate values of the drain–source voltage, $|V_{DS}| \sim 1$ V, and for $|B| < B_{cross}$, the current is lower when charge is deflected into the bulk than when it is deflected into the oxide. In the off-state, charge cannot hop as easily in the bulk as it can at the oxide interface. If the defect density increases, then there will be greater wavefunction overlap between one localized charge and its closest neighbor. The off-state current will be higher than in a sample with low defect density. To stop an avalanche, one would need a higher magnetic field. On the other hand, the higher defect density would reduce the mobility in the on-state.

We will briefly list three possible applications of the magnetoresistive behavior that we have observed: (1) suppression of dark current in a phototransistor, (2) suppression of MOSFET off-state drain–source leakage current, and (3) magnetic field detection.

To reduce the dark current in a phototransistor with high voltage bias, it is reasonable to orient the magnetic field parallel to the substrate, but perpendicular to the current. The incident light would shine on an area of Ge covered by oxide, as illustrated in Fig. 7. At the periphery would be two rectangular magnetic thin films, with the B-field parallel to the substrate and perpendicular to the source–drain axis. The planar B-field would point from one magnetic rectangle to the other, passing through the central, light-accessible region of oxide-covered Ge. The use of magnetization parallel to the plane would

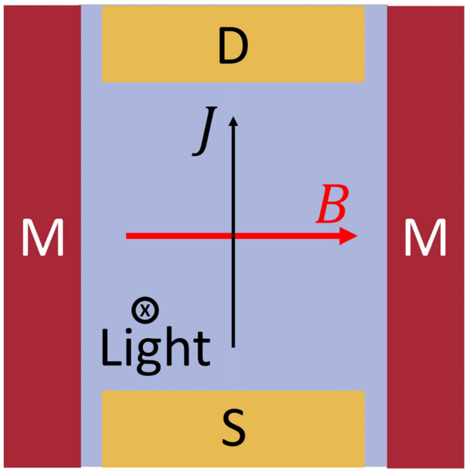

FIG. 7. Phototransistor with suppressed off-state current. Magnets (M) with in-plane magnetic field (B) pointing to the right and perpendicular to the source (S)–drain (D) current (J) suppress hopping current in the dark when carrier density is low. Illumination generates photocarriers with negligible influence from the magnetic field.

simplify device fabrication, with metallization only at the topside of the substrate. In the case of magnetization perpendicular to the plane, the magnetic thin film would have to project its field from the backside of the substrate, to avoid blocking the light shining on the topside. In analogy with Fig. 3(b), under illumination, the current would increase by orders of magnitude and have only a weak dependence on magnetic field. In the dark, the holes get deflected into the bulk Ge (into the page in Fig. 7), where magnetic field-induced suppression of hopping is most effective.

In the same way that magnetic thin films suppress unwanted dark current in a phototransistor, they would also suppress the unwanted off-state current in a MOSFET. In this case, the magnetic film could be co-planar with the gate metal, since one does not have to worry about blocking light, as in the case of the phototransistor. As seen in Fig. 3(b), there is little penalty of reduction of on-state current, for the lowest source–drain voltages, only the benefit of reduced leakage in the off-state. For the highest drain–source voltages, there is a penalty reduction in on-state current, but the benefit reduction in off-state current is orders of magnitude more. Furthermore, one might optimize the large source–drain bias on/off current ratio by eliminating current paths outside the gate area. The device could be diced to the same width of the lateral dimension. More practically, deeply etched trenches could encircle the device. While current could conceivably flow under the trenches, the amount would be negligible compared with the hopping current flowing at the contiguous oxide interface without etched trenches. This would decrease the off-state current, since parallel leakage paths would be blocked, and all leaking holes would be forced to flow under the repulsive positively biased gate.

The phenomena described in this paper could also be exploited to make a cryogenic magnetic field sensor, as others have noted for the case of two-terminal devices. With just one off-state MOSFET, and a scan of the drain–source voltage, one could calibrate the current response for a collection of fixed magnetic fields. One would then have a lookup table to determine the strength of an unknown magnetic field. With a collection of identical MOSFETs, one could apply a different drain–source voltage to each one and have a kind of Geiger-mode detector, in which the unknown magnetic field is determined to lie between the two closely spaced crossover fields of two closely spaced bias voltages. Another option is a bank of non-identical MOSFETs, each with a different channel length and thus a different magnetic field response. Once the coarse estimate of the crossover voltage is determined from the Geiger-mode step, the same voltage would be applied in parallel to the MOSFET bank, to refine the estimate of the magnetic field. The response of the MOSFET to the magnetic field changes only slightly, whether the gate voltage is 0 or +10 V. Thus, the MOSFETs could be replaced by two-terminal devices, with a floating gate, reducing the amount of external control hardware, and associated interconnects.

In summary, we have observed strong magnetoresistive behavior in germanium with platinum germanide contacts and demonstrated that the degree of magnetoresistance can be controlled by both the drain voltage and the gate voltage. By repeating the measurements in three orthogonal orientations of the magnetic field vector with respect to the electric current direction and the plane of the substrate, we have elucidated the role of the oxide interface in hopping conduction and impact ionization. The observed behavior is consistent with earlier theories of magnetic field-induced charge localization in depleted semiconductors, in conjunction with the phenomenon of impact ionization. Applications include low-leakage MOSFETs, phototransistors, and magnetic sensors. One geometric orientation, in which the in-plane magnetization of a thin film is oriented perpendicular to the direction of current flow, is particularly useful for phototransistors.

See the supplementary material for a theoretical framework that others have used to calculate binding energies of donors inside a semiconductor under a magnetic field.[17]

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

D. Lidsky: Conceptualization (lead); Data curation (lead); Formal analysis (lead); Investigation (lead); Methodology (lead); Software (lead); Visualization (lead); Writing – original draft (lead). **T. Hutchins-Delgado:** Investigation (supporting). **P. Sharma:** Funding acquisition (lead); Resources (lead). **V. Dobrosavljevic:** Formal analysis (supporting). **T. M. Lu:** Conceptualization (supporting); Formal analysis (supporting); Funding acquisition (supporting); Investigation (supporting); Methodology (supporting); Resources (supporting); Supervision (lead); Writing – review & editing (lead).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

REFERENCES

[1] B. Jouault, A. Raymond, and W. Zawadzki, "Ionization energy of magnetodonors in pure bulk GaAs," Phys. Rev. B **65**, 245210 (2002).

[2] R. Sladek, "Magnetically induced impurity banding in n-InSb," J. Phys. Chem. Solids **5**, 157 (1958).

[3] J. Schoonus, F. Bloom, W. Wagemans, H. Swagten, and B. Koopmans, "Extremely large magnetoresistance in boron-doped silicon," Phys. Rev. Lett. **100**, 127202 (2008).

[4] J. Schoonus, P. Haazen, H. Swagten, and B. Koopmans, "Unravelling the mechanism of large room-temperature magnetoresistance in silicon," J. Phys. D: Appl. Phys. **42**, 185011 (2009).

[5] Z. Sun, M. Mizuguchi, T. Manago, and H. Akinaga, "Magnetic-field-controllable avalanche breakdown and giant magnetoresistive effects in gold/semi-insulating-GaAs Schottky diode," Appl. Phys. Lett. **85**, 5643 (2004).

[6] J. Lee, S. Joo, T. Kim, K. H. Kim, K. Rhie, J. Hong, and K.-H. Shin, "An electrical switching device controlled by a magnetic field-dependent impact ionization process," Appl. Phys. Lett. **97**, 253505 (2010).

[7] N. Volkov, A. Tarasov, D. Smolyakov, A. Gustaitsev, M. Rautskii, A. Lukyanenko, M. Volochaev, S. Varnakov, I. Yakovlev, and S. Ovchinnikov, "Extremely high magnetic-field sensitivity of charge transport in the Mn/SiO2/p-Si hybrid structure," AIP Adv. **7**, 015206 (2017).

[8] J. Chen, X. Zhang, H.-G. Piao, J. Wang, and Z. Luo, "Enhanced low field magnetoresistance in germanium and silicon-diode combined device at room temperature," Appl. Phys. Lett. **105**, 193508 (2014a).

[9] K. Zhang, H.-H. Li, P. Grünberg, Q. Li, S.-T. Ye, Y.-F. Tian, S.-S. Yan, Z.-J. Lin, S.-S. Kang, Y.-X. Chen *et al.*, "Large rectification magnetoresistance in nonmagnetic Al/Ge/Al heterojunctions," Sci. Rep. **5**, 14249 (2015).

[10] B. Cheng, H. Qin, and J. Hu, "The measured positive and negative magnetoresistance for n-type germanium at room temperature," J. Phys. D: Appl. Phys. **50**, 445001 (2017).

[11] Q.-K. Huang, Y. Yan, K. Zhang, H.-H. Li, S. Kang, and Y.-F. Tian, "Room temperature electrically tunable rectification magnetoresistance in Ge-based Schottky devices," Sci. Rep. **6**, 37748 (2016).

[12] X. He, F.-L. Yang, H.-Y. Niu, L.-F. Wang, L.-Z. Yi, Y.-L. Xu, M. Liu, L.-Q. Pan, and Z.-C. Xia, "Unconventional room-temperature negative magnetoresistance effect in Au/n-Ge: Sb/Au devices," Chin. Phys. B **33**, 037504 (2024).

[13] S. Ohya, S. Tsuruoka, M. Kaneda, H. Shinya, T. Fukushima, T. Takeda, Y. Tadano, T. Endo, L. D. Anh, A. Masago *et al.*, "Colossal magnetoresistive switching induced by d_0 ferromagnetism of MgO in a semiconductor nanochannel device with ferromagnetic Fe/MgO electrodes," Adv. Mater. **36**, 2307389 (2024).

[14] X. He, Z. Xia, H. Niu, Y. Song, Z. Zeng, D. Jiang, Y. Liang, and H. Huang, "Evolution of electrical transport property in ge-based negative differential resistance devices under pulsed high magnetic field," phys. status solidi (RRL)–RRL **16**, 2200165 (2022).

[15] J. Chen, X. Zhang, Z. Luo, J. Wang, and H.-G. Piao, "Large positive magnetoresistance in germanium," J. Appl. Phys. **116**, 114511 (2014b).

[16] D. Lidsky, C. Allemang, T. Hutchins-Delgado, A. James, P. Allen, M. Saleh Ziabari, P. Sharma, A. Bradicich, W.-H. Kuo, S. House *et al.*, "Dual operation modes of the Ge Schottky barrier metal–oxide–semiconductor field-effect transistor," Appl. Phys. Lett. **124**, 233503 (2024).

[17] W. Zawadzki, P. Pfeffer, S. Najda, H. Yokoi, S. Takeyama, and N. Miura, "Experimental and theoretical study of magnetodonors in GaAs and InP at megagauss fields," Phys. Rev. B **49**, 1705 (1994).