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Magnetic-field-controllable avalanche breakdown and giant magnetoresistive effects in Gold/semi-insulating-GaAs Schottky diode

Z. G. Sun,[a] M. Mizuguchi, T. Manago, and H. Akinaga
Synthetic Nano-Function Materials Project and Nanotechnology Research Institute, National Institute of Advanced Industrial Science and Technology, Tsukuba Central 2, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan

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Gold (Au)/semi-insulating (SI)-GaAs Schottky diode was fabricated by the standard photolithography method using wet etching. Magnetic-field-dependent avalanche breakdown phenomena were observed in the current–voltage curves measured under magnetic field. The avalanche breakdown due to impact ionization was postponed to higher electrical field under applied magnetic field. Accordingly, threshold voltages of avalanche breakdown increased with the applied magnetic field. Above 0.2 T, avalanche breakdown was totally quenched. When Au-SI-GaAs Schottky diode was operated above the threshold voltage, giant mangetoresistive effects up to 100 000% were achieved under magnetic field of 0.8 T. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1834733]

Magnetoresistance (MR) effects, especially giant MR (GMR),[1–3] colossal MR,[4] etc., have stimulated great interest of physicists and material scientists, due to its application in magnetic information storage, sensors, and magnetoelectronics.[1–9] The negative GMR effect has been observed in many structures such as antiferromagnetically coupled multiplayers,[1] magnetic granular systems,[2] and tunneling junctions.[3] Recently, GMR effects were also reported in several nonmagnetic materials, for example, the silver chalcogenides,[5] VO_x thin films,[6] single-crystal bismuth thin films,[7] etc. In inhomogeneous semiconductors with metallic inclusions, for example, InSb/Au heterostructure, positive GMR effect with a MR ratio as high as 100 000% at magnetic field of 4 T was observed due to enhanced geometric MR effect.[8] Magnetoresistive switch effect with a huge room-temperature MR more than 1 000 000% at 1.5 T had also been observed in the Sb/MnSb nanoclusters/GaAs system.[9,10] In this letter GMR effect by utilizing magnetic-field-dependent avalanche breakdown phenomena observed in gold/semi-insulating (SI) GaAs Schottky diode is reported. Although the transport properties of SI-GaAs have been intensively studied due to its wide applications as substrates for electrical devices or high power photoconductive semiconductor switches (PCSS) for pulsed power technology,[11–18] little attention has been paid to avalanche breakdown phenomena above a critical field or its magnetic field effects.[11–13]

The Au/SI-GaAs Schottky diodes were fabricated in the following way. SI-(111)B GaAs single-crystal wafer were produced by Mitsubishi Chemical Company in intentionally undoped liquid encapsulated Czochralski method (the mobilities given by the producers range between 5 and $7\times10^4\ \mathrm{cm^2/Vs}$; the resistivity is about $8\times10^8\ \Omega\,\mathrm{cm}$). Granular Au films with nominal thickness of 10 nm were grown on the SI-GaAs surface by 32P molecular-beam epitaxy system. Before the growth of the Au film, surface oxide layer on the SI-GaAs surface was removed by heating in high vacuum, and then 10 nm GaAs buffer layer was grown to flatten the surface. Standard photolithography method using wet etching was applied to fabricate two Au electrodes separated by a micrometer-sized gap (a schematic illustration of the device is shown in Fig. 1, the gap is about 2 μm wide), aqua regia ($3HCl+HNO_3$) was used to etch away the gold film.

The current–voltage ($I-V$) characteristics were measured at room temperature by two-probe method. Typical $I-V$ curve in logarithmic form is shown in Fig. 2, the corresponding electrical field is plotted in the top axis. In the $I-V$ curves several turning points V_1(0.8 V), V_2(12 V), and V_3(32 V) can be clearly observed, as marked in the figure. Up to V_1, there is a linear dependence of $I-V$. The Ohmic $I-V$ characteristic can be ascribed to the fact that SI-GaAs is a relaxation semiconductor, in which dielectric relaxation time of 10^{-4} s is much larger than the recombination lifetimes (below 10^{-8} s).[14] Between V_1 and V_2, the current slowly saturates with increasing voltage which is governed by velocity controlled high field transport mechanism.[15] Within this part current oscillations caused by traveling high-electric-field domains have also been observed previously.[10,15] At V_2, there is a small jump of current, followed by a quick increase of current ($I\propto V^5, V_2<V<V_3$). Much steeper jump with a sudden tenfold increase of current occurs at V_3. Above V_3, current increases in terms of $I\propto V^3$. The sudden increases at V_2 and V_3 can be interpreted within the frame of the impact ionization model.[11–13] The corresponding values of electrical fields, 0.6 and 1.6×10^5 V/cm,

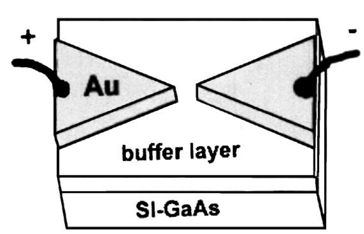

FIG. 1. Schematic illustration of the Au/SI-GaAs Schottky diode used for transport measurements. The two Au electrodes were fabricated on the semi-insulating GaAs by photolithography using the wet-etching method. The gap size is 2 μm.

[a]Author to whom correspondence should be addressed; electronic mail: z-sun@aist.go.jp

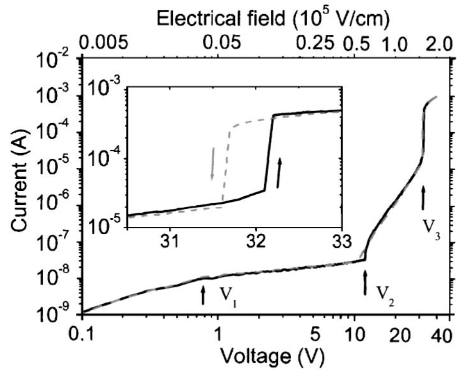

FIG. 2. Current–voltage characteristic curve of Au/SI GaAs devices measured at room temperature. The turning points of the curves are labeled as V_1, V_2, V_3. The inset shows enlarged curves near avalanche breakdown region at V_3.

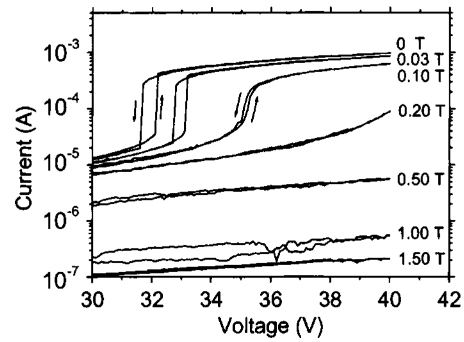

FIG. 3. Room-temperature current–voltage characteristic curve of Au/SI GaAs devices measured under various applied magnetic fields.

are comparable to the previous reported one and sufficient for the impact ionization.[12,13] Above V_2 and V_3, it is the autocatalytic process of impact ionization of shallow impurities that causes the current to increase avalanchelike by several orders of magnitude (avalanche breakdown). V_2 and V_3 are so-called threshold fields of avalanche breakdown. It was believed that intrinsic midgap defects, for example, El2, EL6, etc., may play important roles during the impact ionization.[12] The two sudden increases of current observed at V_2 and V_3 are determined by relative location of Fermi level F_0 in thermal equilibrium and that of trap levels as explained in Ref. 13: F_0 lies between two trap levels E_{t1} and E_{t2}, i.e., $E_{t1}<F_0<E_{t2}$, and $N_{t2}>P_{t1,0}$, where N_{t2} is the concentration of E_{t2} and $P_{t1,0}$ is the concentration of thermally generated trapped holes. The small jump of current at V_2 and the steep increase at V_3 corresponds to filling of E_{t2} level and that of conduction band by the hot electrons, respectively. Furthermore from the inset of Fig. 1, which show the enlarged part of $I-V$ curves near V_3, a clear hysteresis of avalanche breakdown between the increasing and decreasing voltages can be observed. When the voltage is gradually decreased, the system is found to remain at the high current state even when the voltage is much smaller than the breakdown voltage. Such a hysteresis phenomenon is very similar to the "lock on" effect utilized in PCSS device. In PCSS device, a short pulse of light photo-ionizes the GaAs and a carrier avalanche causes a large current that does not "switch off"—unless the bias is significantly reduced.[16] Unlike avalanche breakdown phenomena observed in many other semiconductor devices, which may result in fatal damage to the device, the Au/SI -GaAs Schottky diode exhibits very good endurance and reproducibility: the $I-V$ curves show no significant changes even after long-time repeated measurement.

The avalanche breakdowns occuring at V_3 are found to be strongly magnetic-field dependent. Figure 3 shows the $I-V$ curves measured under various perpendicular magnetic fields. When a small magnetic field was applied, the threshold voltages for the avalanche breakdown shift to a higher voltage. A nearly linear relationship between threshold voltages and the applied magnetic field can be deduced from the measurements. Also the jumps of current due to avalanche breakdown became less and less steep with increasing magnetic field, as clearly reflected in the curves of 0.03 and 0.1 T. Above 0.2 T, no jump driven by the applied voltage could be detected. The increase of threshold voltage with applied magnetic field is quite different from that observed in *n*-GaAs, in which the threshold voltage was found to be almost unchanged with magnetic field.[17] Another effect of the applied magnetic field is to strongly depress the current under high magnetic field. As shown in Fig. 3, when the applied voltage was fixed below the threshold voltage V_3, the current was found to decrease from 10^{-5} A at 0 T to 10^{-7} A at 1.5 T, indicating hundred-fold increase of resistance. Above the threshold voltage V_3 (32 V), the current is found to decrease from 10^{-3} A at 0 T to about 10^{-7} A at 1.5 T, indicating a ten-thousand-fold increase of resistance under the application of 1.5 T magnetic field. It is possible to obtain largest resistance variation at small magnetic field if the operating voltage of Au/SI-GaAs Schottky diode was set just above the threshold voltage. For example, when the voltage was set just above the threshold voltage at 0 T (32 V) but below the threshold voltage at 0.03 T (32.7 V), magnetic field as small as 0.03 T will decrease the current from 5×10^{-4} A to about 2×10^{-5} A.

The strong depression of current under magnetic field of Au/SI-GaAs Schottky diode operating in the high-current avalanche breakdown state implies a huge GMR effect. Figure 4 shows the measured current-magnetic field curve under 33 V and its corresponding MR ratio curves. The MR ratio is defined as MR ratio$=\{R(x)/R(0)-1\}\times100$, Here, R (0) and R (x) are the resistances of the sample at 0 T and x T, respectively. The device was operated in high-current avalanche breakdown state because the operated voltage is higher than the threshold voltage. As shown in the figure, with the increasing magnetic fields the current continuously decreases. A sharp decrease of current occurs at around 0.2 T, above 0.2 T the current is largely depressed. The cor-

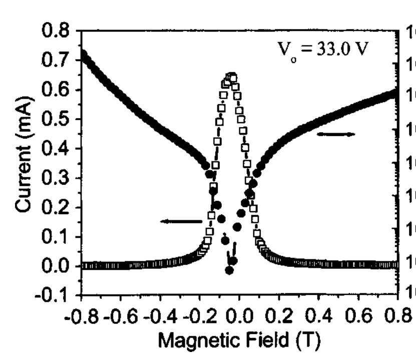

FIG. 4. Current–magnetic field relationship (left axis) and corresponding magnetoresistive ratio curves (right axis) measured at operating voltage of 33 V.

responding MR ratio also shows a quick increase before the 0.2 T. MR ratio reaches 3 000% at 0.2 T. Then MR ratio shows a continuous increase, reaching 100 000% at 0.8 T. The magnetic-field-dependent avalanche breakdown accounts for the huge GMR effect observed in MR curve. Similar to what is observed in *n*-InAs compound, modification of band structure by the magnetic field may be the origin of the shift of threshold voltage and the final quenching of impact ionization.[18] At zero magnetic field, for voltages greater than the threshold voltage the sample is in high current state, indicating a significant concentration of hot electrons with energies above the mobility edge. The application of a magnetic field increases the density of states at the bottom of the lowest Landau level, causing electrons to occupy states with lower and lower energy. Accordingly the current decreases since fewer and fewer electrons can take part in the impact ionization process. Impact ionization vanishes when the concentration of electrons thermally activated above the mobility edge is insufficient to trigger the avalanche, this results in a quick decrease of current and disables the breakdown.

In conclusion, magnetic-field-dependent avalanche breakdown phenomena were observed in the Au/SI-GaAs Schottky diode. Magnetic field postpones the avalanche breakdown to high electrical field. At small magnetic field the threshold voltages linearly increase with applied magnetic field. At high magnetic field, the avalanche breakdown is totally quenched. When operated above the threshold voltage, GMR effects up to 100 000% are observed when a magnetic field of 0.8 T is applied. Hugh GMR effect, very good endurance, and reproducibility imply that Au/SI-GaAs Schottky diode may be applied as a magnetic field sensor.

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