Magnetic tunnel transistor with a silicon hot-electron emitter

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We report on a modified magnetic tunnel transistor having a silicon tunnel emitter. The device has the structure Si/Al_2O_3/base/Si with a spin-valve metal base, a Schottky barrier collector, but a silicon emitter separated from the base by a thin tunnel oxide. The energy of the hot electrons injected from the Si emitter into the base can be tuned by the emitter bias, which drops partly over the Si depletion region. Compared to a magnetic tunnel transistor with a metal emitter, the voltage drop over the thin tunnel oxide is reduced, enabling stable device operation at higher biasing conditions. We fabricated devices with a magnetocurrent up to 166% and a steeply enhanced transfer ratio reaching 6×10^{-4} at an emitter current of 200 mA. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2084335]

Spintronics as well as magnetic data storage rely on magnetic devices that exhibit an electrical current that depends strongly on a magnetic field. Amongst the various devices, those combining semiconductors and ferromagnetic metals are particularly interesting. An example is the spin-valve transistor (SVT), a three-terminal device with the emitter/base/collector structure typical of a bipolar transistor, but the base region is metallic and contains two ferromagnetic layers separated by a nonmagnetic spacer.[1–3] The two ferromagnetic layers act as a polarizer and analyzer of hot-electron spins, such that the relative orientation of the magnetization of the two layers controls the transmission of the base. The output (collector) current of the SVT therefore depends on the magnetic state of the base, and a large magnetocurrent up to 350% has been obtained at room temperature.[2,4] In addition, the device has proven valuable for the study of the physics of spin-dependent hot-electron scattering.[3]

In an SVT with a semiconductor-metal-semiconductor (SC/M/SC) structure, the hot-electron energy is fixed as it is determined by the height of the Schottky barrier between emitter and base. In a related device, the magnetic tunnel transistor (MTT), this limitation was overcome by using a tunnel junction as the emitter, yielding an M/I/M/SC structure.[5] The thin insulator (I) acts as a tunnel barrier, injecting hot electrons into the metal base at an energy given by the tunnel bias voltage between the metal emitter and base. The tunability of the hot-electron energy allows spectroscopic studies, as well as operation at higher energies, while the MTT offers the same magnetic sensitivity as the SVT (at a comparable thickness of the ferromagnetic base layers) since the spin sensitivity originates from the same spin filtering of hot electrons.[6–8]

For the MTT, a concern is the reliability of the ultrathin tunnel oxide under the required large bias (1–2 V) and large current density.[9,10] We have therefore considered a modified version of the MTT in which the metal emitter electrode is replaced by a semiconductor. The so-called MIS-MTT has the structure SC/I/M/SC, where the emitter-base junction constitutes a metal-insulator-semiconductor (MIS) diode.[11] When a forward bias voltage is applied across the MIS diode, hot electrons from the *n*-type SC are injected by tunneling into the metal base. Since the voltage drops partly across the SC depletion region and partly across the tunnel barrier, the voltage stress on the ultrathin tunnel oxide is reduced. However, the hot-electron energy is still tunable, as the voltage fraction that drops across the tunnel insulator raises the conduction band minimum at the SC surface with respect to the Fermi level of the base metal.[11]

Here we describe the fabrication of the MIS-MTT and demonstrate the magnetic and electrical operation. We fabricated two kinds of MIS-MTT that differ only in the metal used for the collector Schottky barrier: Si/Al_2O_3/Co/Au/$Ni_{80}Fe_{20}$/Au/Si (Au device) and Si/Al_2O_3/Co/Au/$Ni_{80}Fe_{20}$/Cu/Si (Cu device). For the Au device the collector Schottky barrier height (0.8 eV) is larger than the equilibrium barrier height (0.74 eV) of the Si/Al_2O_3/Co MIS emitter, such that no transmitted current is expected at low bias. However, with increasing emitter bias we can tune the hot-electron energy to above the threshold for collection. The Cu device with a lower collector barrier height (0.65 eV) should exhibit a larger transmission.

The fabrication of the MIS-MTT is similar to that of the SVT as described in detail previously[3,12] and involves the vacuum metal bonding technique. We start with standard cleaning of the silicon-on-insulator (SOI) emitter. After surface oxide removal using an HF etch, the emitter is clipped onto one of the two arms of the vacuum bonding tool. The Al_2O_3 layer is prepared by evaporation of 0.8 nm Al in ultrahigh vacuum, followed by a natural oxidation in 200 Torr oxygen ambient for 120 min in a connected load lock chamber. The procedure is repeated once more to obtain a 2 nm oxide. Next, the metal stack consisting of Co(3 nm)/Au(6 nm)/$Ni_{80}Fe_{20}$(3 nm)/Au(2 nm) was deposited. The last Au layer is used to protect the ferromagnetic metal from oxidation in air, when the robot is briefly taken out of the vacuum chamber for mounting the collector Si piece on the other robot arm. Then, 2 nm Au is deposited simultaneously on the emitter and collector parts and the bonding is initiated. For the Cu device, the bonding was done using Cu and the oxide was prepared in a different way, namely by evaporation of 2 nm Al_2O_3 from an E-gun fol-

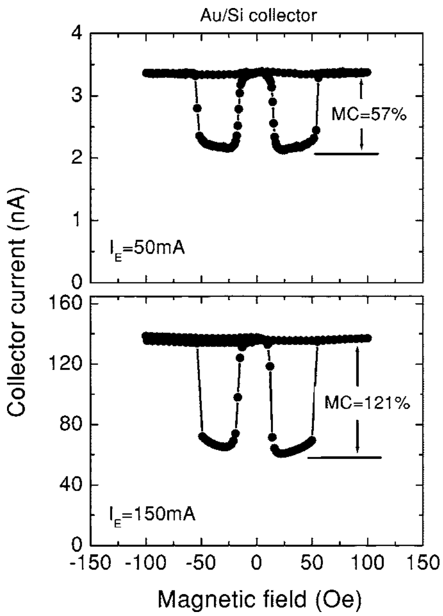

FIG. 1. Collector current vs magnetic field of a $Si/Al_2O_3/Co/Au/Ni_{80}Fe_{20}/Au/Si$ MIS-MTT at I_E=50 mA (top panel) and 150 mA (bottom panel) at 90 K, respectively.

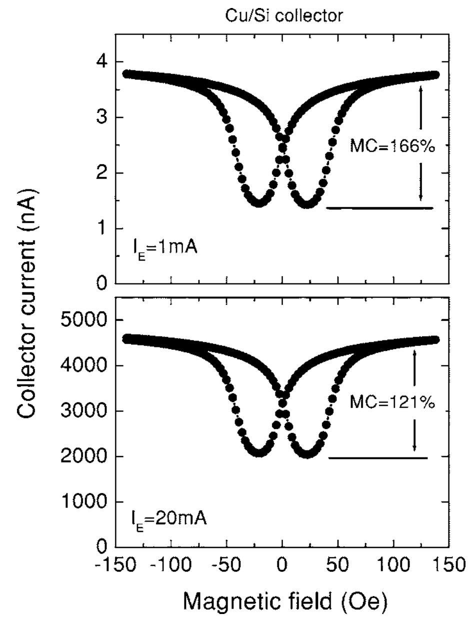

FIG. 2. Collector current vs magnetic field of a $Si/Al_2O_3/Co/Au/Ni_{80}Fe_{20}/Cu/Si$ MIS-MTT at I_E=1 mA (top panel) and 20 mA (bottom panel) at 90 K, respectively.

lowed by natural oxidation. The processing into electrical devices (350×350 μm^2) is identical to that described previously for the SVT,[3,12] except for the use of cryogenic dry etching for removal of the handle silicon of the emitter SOI wafer. Magnetotransport characterization was carried out using a three-terminal common base setup at a temperature of 90 K. The maximum value of the emitter current was 200 mA, which corresponds to a moderate current density below 200 A/cm^2.

In Fig. 1, the collector current I_C as a function of applied magnetic field is shown for the device with Au/Si collector for two different values of the emitter current I_E. Qualitatively the behavior is similar to that of the SVT and conventional MTT. There is significant magnetic field dependence with a larger collector current for large magnetic field corresponding to the parallel (P) magnetization of the Co and $Ni_{80}Fe_{20}$ layers, and a smaller collector current for the field regions with antiparallel (AP) magnetization alignment. The relative change of collector current (the magnetocurrent $MC=(I_C^P-I_C^{AP})/I_C^{AP}$) is 57% and 121% for an emitter current of 50 and 150 mA, respectively. Figure 2 shows similar characteristics for the device with a Cu/Si collector but at an emitter current of 1 and 20 mA, with a magnetocurrent of 166% and 121%, respectively. Note the different switching behavior of the ferromagnetic layers for the Au and Cu device. This is caused by unintentional variations in the magnetic anisotropy of the layers. This can be due to differences in the anisotropy induced during growth, due to difference in the roughness, or due to slight variations of the thermal exposure during the device processing, in particular, during the etching of the handle Si of the emitter SOI wafer.

For both MIS-MTT devices we observe that the transfer ratio (I_C/I_E) is larger for the larger emitter current. A complete set of data is shown in Figs. 3 and 4, where the collector current, MC, and transfer ratio are plotted as a function of the emitter current for the device with Au/Si and Cu/Si collector, respectively. When I_E is increased, the collector current for both devices shows a nonlinear increase (top panels). The transfer ratio is strongly enhanced by more than two orders of magnitude for the device with Au/Si collector (Fig. 3, bottom panel) and about one order of magnitude for the device with Cu/Si collector (Fig. 4, bottom panel). The enhancement of the transfer ratio with emitter bias proves the working principle of the MIS-MTT and demonstrates that the energy of the hot electrons injected from the MIS structure grows as the emitter voltage (current) is increased. This behavior is similar to that of a conventional MTT where the transfer ratio increases with emitter bias due to the larger hot-electron energy,[7,13] but different from the behavior of a SVT where the hot-electron energy is constant and the trans-

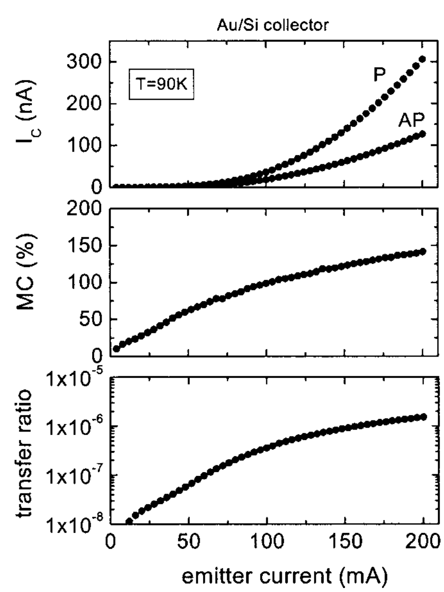

FIG. 3. Collector current (in AP and P state), magnetocurrent (MC), and transfer ratio (I_C/I_E) of a $Si/Al_2O_3/Co/Au/Ni_{80}Fe_{20}/Au/Si$ MIS-MTT. T=90 K.

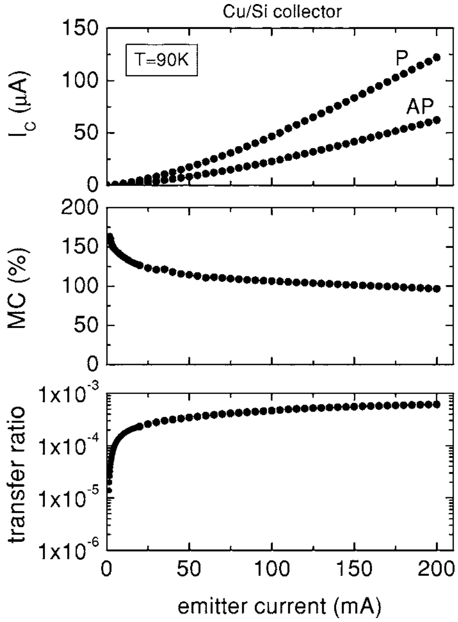

FIG. 4. Collector current (in AP and P states), magnetocurrent (MC), and transfer ratio (I_C/I_E) of a $Si/Al_2O_3/Co/Au/Ni_{80}Fe_{20}/Cu/Si$ MIS-MTT. T=90 K.

fer ratio does not depend on the emitter bias or current.[14]

From electrical characterization of the $Si/Al_2O_3/Co$ MIS diode we deduced a barrier height of 0.74 eV under equilibrium conditions (i.e., at zero applied bias). Therefore, at low bias the emitter injects hot electrons at an energy which is *lower* that the barrier height of the Au/Si combination (0.8 eV). Hence the low transmission below 10^{-8} for this device at small I_E. At small emitter bias (current), the resistance of the MIS diode is dominated by the depletion region in the Si emitter, which therefore absorbs most of the applied voltage. As the voltage increases, the depletion region is gradually reduced. As a result, the fraction of the voltage that drops over the tunnel barrier increases, thereby increasing the energy at which hot electrons are emitted into the base. This produces the observed increase of the transfer ratio by several orders of magnitude. The behavior of the device with Cu/Si collector is different and the transfer ratio is about two orders of magnitude larger. This is due to the lower Schottky barrier height (0.65 eV) of the Cu/Si collector, which is below the energy of 0.74 eV at which the hot electrons are emitted into the base at low emitter bias (current). Thus for this device the hot-electron energy is always well above the conduction band minimum of the Si collector, where more states are available for transmission.[3,15] The output current of the Cu device reaches $I_C^P = 122\ \mu A$ at 200 mA emitter current, which is equivalent to an emitter current density of 160 A/cm^2. The corresponding transfer ratio is 6×10^{-4}. This is larger than the value of 1.7×10^{-4} previously reported for the SVT.[14] This is a promising result given that it is the first generation of MIS-MTT devices, and we believe that further improvement of the device properties can be achieved by optimizing the MIS diode preparation and tuning the insulator thickness.

With respect to the MC of the devices, we note a strikingly different trend for the devices with Au/Si and Cu/Si collector (middle panels of Figs. 3 and 4, respectively). For the device with a Cu/Si collector (Fig. 4) we observe a behavior similar to that of a MTT with a metal tunnel emitter,[7] namely, the largest MC of 166% at low emitter bias and a gradual reduction of the MC with increasing emitter bias. The MC stabilizes at a value of about 100% at an emitter current of 200 mA. In contrast, the device with a Au/Si collector (Fig. 3) shows an MC that vanishes at small emitter bias, and steadily *increases* as the emitter current increases. The largest value of the MC is 142% at I_E=200 mA. Quite likely this unexpected behavior is related to the difference in the energy of the hot electrons with respect to the collector Schottky barrier height, as explained above. For the Cu/Si device, the hot-electron energy is always above the collector barrier, resulting in behavior similar to that of an MTT. For the Au/Si device, however, the hot electrons are injected near the threshold for collection, where one is most sensitive to scattering processes involving small energy loss. Additional information about the spin-dependent scattering mechanisms may therefore be expected, although a detailed understanding is lacking and requires further investigation.

In conclusion, a modified version of the MTT with a silicon hot-electron emitter has been presented. The principle of the MIS-MTT, the ability of the MIS injector to provide hot electrons with tunable energy, and stable device operation at high emitter current has been demonstrated. Devices with magnetocurrents up to 166% and a steeply enhanced transfer ratio reaching 6×10^{-4} at an emitter current of 200 mA are achieved, while unexpected behavior of the magnetocurrent was observed for hot-electron injection near the collection threshold.

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