Excitation and transport of hot holes in a magnetic tunnel transistor

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Spin-dependent transport of nonequilibrium holes has been investigated using a magnetic tunnel transistor in which a magnetic tunnel junction is combined with a *p*-type semiconductor. The device can be used for direct hole injection and collection, or in reverse mode in which holes are created by inelastic decay of injected hot electrons via electron-hole pair generation. In the latter case, the collected hole current is larger, and a magnetocurrent (MC) of 90% is observed at an emitter bias of −0.8 V. This positive and large MC indicates that hot holes generated by hot electrons of majority spin contribute mostly to the collector current. © *2006 American Institute of Physics.*
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Spin-dependent transport of nonequilibrium, so-called hot electrons, has been extensively studied with various techniques.[1–5] It has been shown that hot electrons of majority spin are transmitted preferentially in a ferromagnetic (FM) layer due to the large difference in attenuation length of the majority and minority spins. This leads to spin-filtering effect in a FM layer and gives rise to a large magnetic sensitivity in FM/semiconductor hybrid structures such as spin-valve transistors and magnetic tunnel transistors.[4–8] Recently, the spin dependence of *hole* transmission at energy *below* the Fermi level has been demonstrated using ballistic hole magnetic microscopy.[9] Using this scanning tunneling microscopy based technique, the attenuation length of holes and spin filtering of hot holes in a NiFe/Au/Co/*p*-type Si structure were reported. Moreover, the technique was used for magnetic imaging with resolution below 30 nm.[10]

In this study, we report on the realization of a solid-state device that utilizes spin-dependent transport of hot holes. We have fabricated a *p*-type magnetic tunnel transistor (MTT) device by combining a magnetic tunnel junction and a *p*-type semiconductor. A MTT is a three-terminal hybrid device consisting of a tunnel emitter, a FM base, and a semiconductor collector. Figure 1 shows the schematic energy band diagram of the *p*-type MTT device that has a $Ni_{80}Fe_{20}/Al_2O_3$ emitter, a Co base, and a collector of a Schottky contact between Au and *p*-type Si. So far, the MTT has been fabricated with *n*-type semiconductors in which hot-electron transport is used.[6,7] By replacing an *n*-type semiconductor with a *p*-type one, we have successfully developed a MTT device based on hot-hole transport. As transport occurs in states below the Fermi level of the base, the *p*-type MTT can be used to probe spin-dependent transmission of hot carriers below the Fermi level whereas the *n*-type MTT probes hot-electron transport. Also, the hot carriers injected from the emitter originate from different states in *n*- and *p*-type MTT's, which allow us to probe the tunnel spin polarization of different states. The two types of MTT devices therefore are complementary.

We examine two different methods for creating hot holes in the base of the MTT. First, hot holes can be directly injected from the emitter by a tunneling process (direct mode), in which case the emitter is biased positive with respect to the base. Interestingly, one can also produce holes by changing the polarity of the emitter bias,[10] in which case hot electrons are injected into the base layer. Energy relaxation of the hot electrons via electron-hole pair excitation then creates hot holes (reverse mode, see Fig. 1). The hot holes are transmitted through the base layer and collected in the valence band of *p*-type Si provided the holes retain sufficient energy and have the proper momentum to overcome the Schottky barrier of the collector.

We have investigated collector hole currents as a function of emitter bias voltage and their magnetic field dependences. The hole current increases with increasing emitter bias voltage of both positive and negative polarities. It is found that the hole current is larger in the reverse mode. We
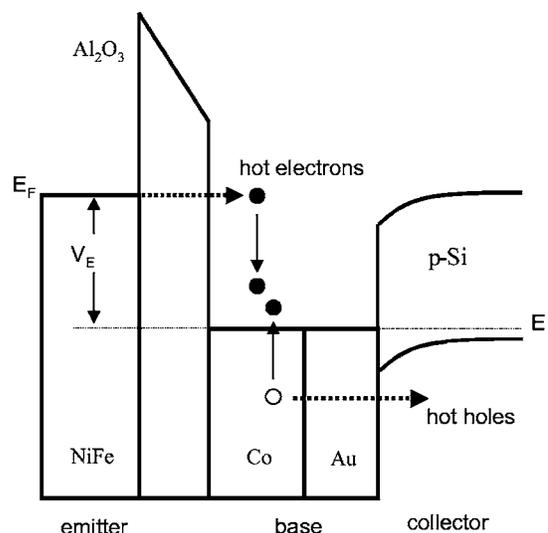

FIG. 1. Schematic energy diagram of a *p*-type MTT in reverse mode. The *p*-type MTT consists of a $Ni_{80}Fe_{20}/Al_2O_3$ emitter, a Co base, and a Au/*p*-type Si collector. Hot electrons are injected from the emitter into the base by a spin-polarized tunneling process. Inelastic scattering of the hot electrons in the base creates hot holes via electron-hole pair generation. The hot holes are transmitted through the base layer and collected in the valence band of *p*-type Si provided the holes retain sufficient energy and have the proper momentum to overcome the collector Schottky barrier.

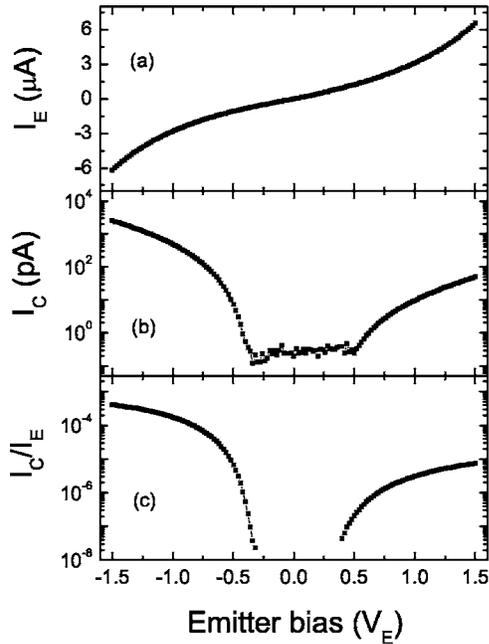a)Electronic mail: b.g.park@el.utwente.nl

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FIG. 2. Emitter current (a), collector current (b), and ratio of the collector and emitter currents (c) as a function of emitter bias voltage for a MTT of p-Si/Au(7 nm)/Co(8 nm)/Al$_2$O$_3$(2.5 nm)/Ni$_{80}$Fe$_{20}$(10 nm)/Au(10 nm) structure. Note that the sign of I_C is positive for all emitter bias voltages. Measurement was done at 82 K.

observe a clear magnetic dependence of the hole current, resulting in a current change of 90% at an emitter bias of −0.8 V.

The MTT of $p-$Si/Au(7 nm)/Co(8 nm)/Al$_2$O$_3$ (2.5 nm)/Ni$_{80}$Fe$_{20}$(10 nm)/Au(10 nm) was deposited by e-beam evaporation in a molecular beam epitaxy system at a base pressure of 10^{-10} mbar. The films were grown on a lithographically defined area of a p-type Si wafer, surrounded by a thick SiO$_2$ to reduce the base-collector contact area and eliminate edge leakage current across the collector diode. A high quality Schottky barrier of 0.3±0.03 eV was formed at the p-type Si/Au interface. The Al$_2$O$_3$ tunnel barrier was formed by plasma oxidation of a 2 nm Al layer. The MTT devices were fabricated using standard photolithography, ion beam etching, and lift-off techniques. The diameters of the junction area and the base-collector diode were 10 and 20 μm, respectively. Transport measurements were conducted using a four-point geometry for the emitter to the base tunnel junction, where the base is connected to ground, and a separate Ohmic contact to the back of the Si collector. All measurements presented here were done at 82 K to eliminate leakage current across the collector diode with low Schottky barrier height.

Figure 2 shows the emitter current I_E (a), the collector current I_C (b), and the ratio of the collector and emitter currents I_C/I_E (c) as a function of emitter bias voltage. The emitter current increases nonlinearly with emitter bias voltage, which is a typical I-V characteristic of a tunnel junction. The junction resistance is around 500 kΩ at low bias and decreases to 350 kΩ at 1 V. The emitter current is a few microampere at an emitter bias of the order of 1 V. The positive sign of the emitter current here corresponds to the hole current flowing from emitter to base. Hence, holes

(electrons) are injected into the base at the positive (negative) emitter bias.

Figure 2(b) shows that when the bias voltage is small, the collector current is below the detection limit of measurement system (a few tenths of picoampere). However, I_C abruptly increases at an onset voltage of around 0.3±0.1 eV, corresponding to the Schottky barrier height of the p-type Si/Au contact. The hole current increases with an increase of the bias voltage and reaches +2.5 nA(+50 pA) at a bias voltage of −1.5 V(+1.5 V). Since the emitter current is nonlinear, the ratio of collector and emitter currents plotted in Fig. 2(c) shows the proper bias voltage dependence of the hole current. I_C/I_E increases abruptly just above the onset voltage and reaches $4 \times 10^{-4}(\sim 10^{-5})$ at a bias voltage of −1.5 V(+1.5 V). The increase of I_C/I_E with bias is due to the large number of available states in the valence band of the semiconductor at higher energies.

The *same sign* of the collector current with both positive and negative emitter bias polarities indicates hole current flowing from the base into the p-type semiconductor in both cases. Interestingly, the hole transmission is larger with negative emitter bias (reverse mode), in which hot electrons are injected and holes are generated by inelastic decay of the hot electrons, compared to the case of positive bias (direct mode) where hot holes are directly injected by the tunneling process. This is consistent with the results observed in the ballistic hole emission microscopy.[9,10] This can be rationalized as follows. The attenuation length of hot holes is less than 1 nm in a Co layer,[9] which is two to six times shorter than that of hot electrons.[3,5] In the direct mode, the injected holes from the emitter attenuate throughout the 8 nm Co base layer; therefore, only a small amount of holes retains enough energy to overcome the Schottky barrier of the collector diode. However, in the reverse mode, holes are created everywhere in the Co layer by inelastic scattering of hot electrons. While holes created near the tunnel barrier/Co interface attenuate significantly, holes created close to the Co/Au interface can reach the collector. This explains why the hole current in the reverse mode is larger than that in the direct mode.

Figure 3 shows the collector current versus the magnetic field in the reverse mode, at an emitter bias voltage of −0.8 V. At large magnetic fields, the two magnetic layers have their magnetization directions aligned parallel. This gives the largest collector current of 154 pA. When the magnetic field is reversed and reaches a field region where the magnetizations of two FM layers are antiparallel, the collector current reduces to 81 pA. This results in a magnetocurrent (MC) of 90%. Here, MC is defined as $(I_C^P - I_C^{AP})/I_C^{AP}$, where P and AP refer to the parallel and antiparallel alignments of two magnetic layers, respectively. The asymmetry in the magnetic switching originates from the fabrication process of the MTT, which involves ion beam etching to define the emitter tunnel junction. This frequently introduces irregularities at the edges of the FM emitter that can act as pinning sites for magnetic domains.

The positive MC may come as a surprise. The hole current is proportional to the number of electron-hole pairs generated. Since hot electrons of minority spin are much more
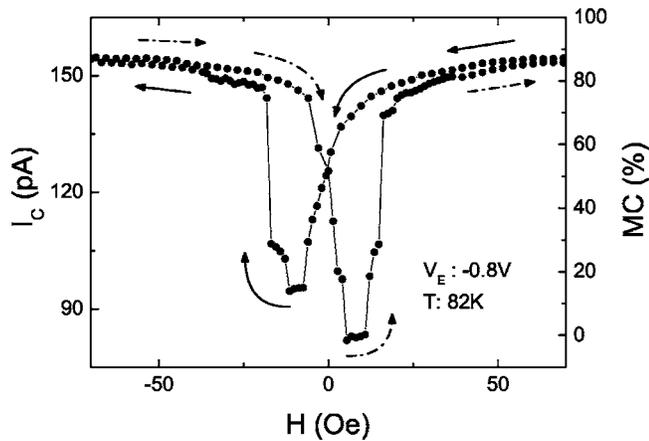
FIG. 3. Collector current vs magnetic field for a *p*-type MTT of *p* -Si/Au(7 nm)/Co(8 nm)/Al$_2$O$_3$(2.5 nm)/Ni$_{80}$Fe$_{20}$(10 nm)/Au(10 nm) structure at a bias voltage (V_E) with −0.8 V and at 82 K. The arrows indicate the magnetic field sweep direction.

strongly scattered in the FM base as compared to those of majority spin, the number of created holes is dominated by the electrons of minority spin in the base. As the tunnel current from the Ni$_{80}$Fe$_{20}$/Al$_2$O$_3$ interface is positively spin polarized, more minority spin electrons are injected into the base in the antiparallel state. A larger hole current is then expected in the antiparallel state, which would result in a negative MC. However, the attenuation length of holes and the base layer thickness should be taken into account. The base Co layer of 8 nm in the MTT is quite thick as compared to the attenuation length of hot holes. For thick base layer, only holes created close to the collector can contribute to the collector current. Due to their weaker attenuation, hot electrons of majority spin in the base generate holes deep in the base layer. The hole current is therefore dominated by the number of majority spin hot electrons in the base. Minority hot electrons create holes near the interface with the tunnel barrier which are strongly attenuated as they pass through the base Co layer, giving only a small contribution to the collector current. This is the reason why the *p*-type MTT with a thick base shows a positive MC in the reverse mode.

A MC of 90% in the *p*-type MTT is a comparable value to that obtained from a similar *n*-type MTT structure in which spin-polarized hot electrons are collected after spin filtering in the FM base.[11] The MC of a MTT depends on the polarization of tunnel current from the emitter and spin asymmetry in the base transmission. The tunnel spin polarization of NiFe/Al$_2$O$_3$ of 32% was determined in the *n*-type MTT.[11] The injected hot-electron current in the *p*-type MTT may have the same spin polarization value since the same FM/tunnel barrier emitter is used. A MC of 90% and a spin polarization of 32% correspond to a spin asymmetry in the base transmission close to unity. This indicates that holes generated by hot electrons of majority spin in the base dominate the collector current.

In conclusion, we have successfully fabricated a MTT device operating with hot hole transport. A hole current is created by inelastic decay of injected hot electrons or by direct hole injection. The *p*-type MTT in reverse mode shows a positive MC of 90% at an emitter bias voltage of −0.8 V.

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