Spin-valve transistors with high magnetocurrent and 40 μA output current

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The electrical characteristics of silicon-based spin-valve transistors are reported, focusing on how the output current and magnetocurrent depend on the magnitude of the emitter current. Transistors with a different combination of Schottky barriers (Si/Au and Si/Cu) were used. The collector current rapidly increases with emitter current, without significant loss of magnetocurrent. Spin-valve transistors with magnetocurrent around 400% and high output current up to 40 μA are obtained. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1687258]

The control of electron spins in semiconductors and their hybrid structures is at the heart of the rapidly developing field of spintronics. One of the devices that were successfully demonstrated is the spin-valve transistor (SVT), a hybrid semiconductor/ferromagnet device that exhibits large room temperature magnetocurrent (MC) up to 400% in small fields.[1–4] While the SVT has provided significant progress in the understanding of spin-dependent transport of hot electrons in ferromagnetic thin film structures,[4] the current transfer ratio (collector current I_C divided by emitter current I_E) has so far been limited to about 10^{-4}. The result is a relatively low output current, which needs to be improved. One of the options is the magnetic tunnel transistor[5] (MTT), a device that is derived from the SVT and differs in the use of a tunnel junction as the emitter, instead of a Schottky barrier. This allows higher hot-electron energy and a reduction of the number of metal layers and interfaces in the transistor base, which are both beneficial for the base transmission.[4,6] Therefore, the MTT should, at least in principle, allow significantly higher current levels to be obtained.

Unfortunately, the improvement as compared to the state-of-the-art SVT's has been only modest. Current transfer ratios around 10^{-3} have been obtained in MTT's that have only a single ferromagnetic layer in the base, with on top a tunnel insulator and a ferromagnetic transition metal emitter electrode.[7] The emitter current is spin polarized due to spin-dependent tunneling, but the MC is only 70–90% as it is limited by the finite tunnel spin polarization of the emitter.[4] This limitation does not exist for MTT's with two ferromagnetic layers (i.e., a spin valve) in the base, in which case the emitter current is injected by tunneling from a nonmagnetic metal as emitter electrode.[8,9] This type of MTT can have MC comparable to that of the SVT (400–600%) for appropriately chosen thickness of the ferromagnetic layers. However, the transfer ratio is reduced[9] to about 3×10^{-4}, which is only three times that of the SVT. Furthermore, there is a basic difference in the variation of the output current of both devices when the emitter current (or voltage) is increased. For the MTT, an increase of the emitter voltage leads to a rapid increase of the output collector current, but at the expense of a significant reduction in the MC.[5,7] In this work we show that for the SVT, the transfer ratio and MC are insensitive to the emitter current, because the energy of the hot electrons injected into the base is only weakly dependent on the emitter voltage. We shall demonstrate that the emitter current can be increased without significant loss of magnetocurrent, such that spin-valve transistors with magnetocurrent around 400% and high output current up to 40 μA are obtained.

We have used two of the SVT's for which room temperature data at low emitter current were previously reported.[6] The devices have Si as emitter and collector and the following base: Au (20 Å)/$Ni_{80}Fe_{20}$ (30 Å)/Au (70 Å)/Co (30 Å)/Au or Cu (40 Å). One SVT has a Si/Au barrier for emitter as well as collector, such that the barrier height difference is negligible (0.01 eV). The other has a Si/Cu collector barrier that is 0.13 eV lower than the Si/Au emitter barrier. The active device area is $350\times350\ \mu m^2$. Further details can be found in Ref. 6. Measurements presented here are performed at 100 K in constant current mode for emitter current up to 250 mA. This is much larger than used before, but still an order of magnitude below the current at which device breakdown occurs.[10] The maximum applied emitter voltage is about 2.5–3 V and drops mostly over the ohmic back contact to the diode. The maximum voltage across the Schottky barrier itself is estimated to be 0.8 V. No bias voltage was applied across the collector diode. The magnetocurrent is defined as $MC=(I_C^P-I_C^{AP})/I_C^{AP}$, where I_C^P and I_C^{AP} refer to the collector current for parallel (P) and antiparallel (AP) states of the spin valve (hereafter denoted as sv). The transfer ratio is defined as I_C^P/I_E.

Figure 1 shows the results for the SVT with Au/sv/Cu base. As can be seen in the top panel, the collector current increases approximately linearly with emitter current and reaches values up to 44 μA. Since the increase is approximately equally strong for P and AP magnetic states of the spin-valve base, the resulting MC (middle panel) is only

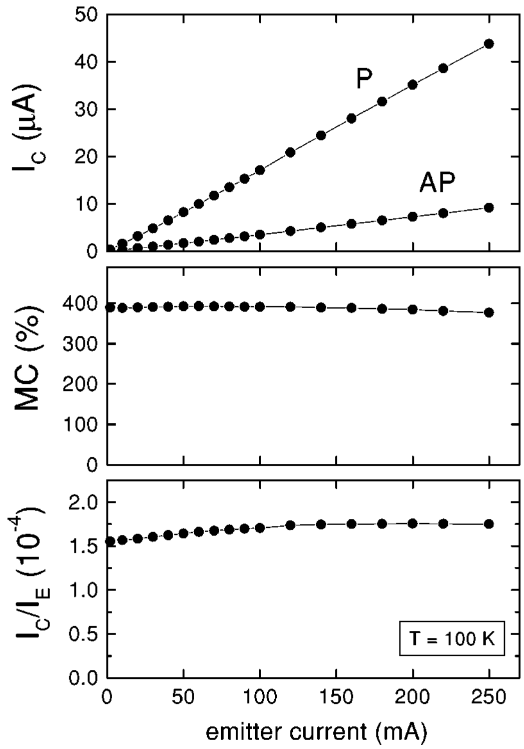

FIG. 1. Collector current, MC, and transfer ratio as a function of emitter current for a SVT with Si/Au/NiFe/Au/Co/Cu/Si structure. $T = 100$ K.

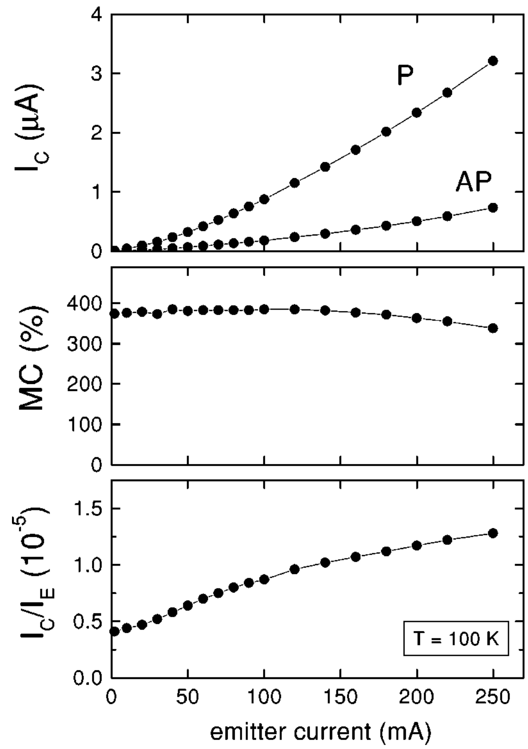

FIG. 2. Collector current, MC, and transfer ratio as a function of emitter current for a SVT with Si/Au/NiFe/Au/Co/Au/Si structure. $T = 100$ K.

weakly reduced and remains around 400% up to the largest emitter current. The transfer ratio of the SVT is 1.55×10^{-4} at low current, and increases slightly to 1.75×10^{-4} at 250 mA of emitter current (bottom panel). Thus, we find that the main features of the SVT are only very weakly dependent on the emitter current, and that the collector current of the SVT can be increased without significant loss of MC. The data convincingly show that the collector current of the spin-valve transistor is by no means limited to the nanoampere regime, but that a high output current above 40 μA and large magnetocurrent around 400% can be obtained.

The results can be understood by considering how a voltage affects the current injected across a Schottky barrier.[11] For diodes on Si with the low doping (1–10 Ωcm) used here, transport is dominated by thermionic emission. For an ideal Schottky barrier all the applied voltage drops over the semiconductor, such that the energy barrier as seen by carriers coming from the Si is reduced and an emitter current is established. However, the maximum of the energy barrier, when measured with respect to the Fermi level in the *metal base*, does not change. Since the barrier maximum determines the energy of the injected hot electrons, an increased emitter voltage produces a larger number of injected electrons, but no change in their energy. This explains why the collector current is enhanced without significant change in the MC or transfer ratio.

The measured ideality factor (1.02) deviates slightly from unity due to the effect of image forces[11] on the barrier height. For Si/Au diodes the effect is typically of the order of 10–20 meV, depending on the electric field at the Au-Si interface.[11] When the diode is forward biased, the barrier maximum is enhanced. However, the 10–20 meV change is small compared to the energy of the hot electrons injected across a Si/Au Schottky barrier of 0.83 eV. This explains the weak but measureable increase of the transfer ratio at larger emitter current.

For a SVT with Si/Au barriers for emitter as well as collector, the hot-electron energy is comparable to the height of the collector Schottky barrier. In that case electrons enter states near the bottom of the conduction band of the collector Si and one may expect that a slight change of the hot-electron energy has a more pronounced effect on the transfer ratio. This is indeed what is observed for the SVT with Au/sv/Au base, for which data are presented in Fig. 2. When the emitter current is raised to 250 mA, the MC remains close to 400%. However, the collector current increases more than linearly and there is a significant increase of the transfer ratio by about a factor of 3. The different behavior as compared to the SVT with Au/sv/Cu base (Fig. 1) is not due to a difference in emitter Schottky barrier, since the barrier height (0.83 eV) and ideality factor (1.02) are identical for both SVT's. Note that the SVT with Au/sv/Au base has a smaller transfer ratio ($\approx 10^{-5}$) than the SVT with Au/sv/Cu base, due to the larger density of available states in the collector conduction band for the latter, as noted previously.[6]

The difference in sensitivity of both SVT's to small changes in the hot-electron energy is also reflected in the temperature dependence of the transfer ratio (Fig. 3). For the Au/sv/Cu base, the transfer ratio is reduced from 1.6×10^{-4} at 100 K to about 1×10^{-4} at room temperature (the sudden increase near 290 K is an artifact due to the onset of edge leakage currents in the Si/Cu collector diodes). The

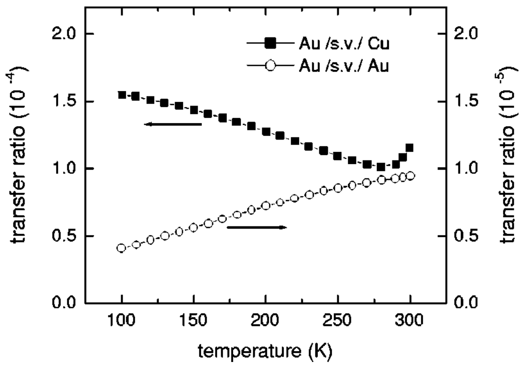

FIG. 3. Transfer ratio vs temperature for two SVT's with Si/Au emittter Schottky barrier and identical spin valve, but different collector barrier, respectively, Si/Au (open symbols) or Si/Cu (solid symbols).

decay of the base transmission at higher temperature is well understood, and is due to the reduction of the hot-electron attenuation length due to enhanced scattering by thermal spin waves in the ferromagnetic layers.[3,12] Since an identical spin valve was used, one would also expect to see a decay of transfer ratio for the other SVT with Au/sv/Au base. However, Fig. 3 shows just the opposite, i.e., a rather large increase of transfer ratio from 0.4×10^{-5} at 100 K to 1×10^{-5} at room temperature. The enhanced base transmission can be explained by an increase of the hot-electron energy, in this case induced by a change in temperature. From the equations of thermionic emission, it can easily be seen that for a Schottky barrier of height Φ_B most of the injected electrons have energies between Φ_B and Φ_B+3kT, where $3kT$ increases from ≈ 25 meV to ≈ 75 meV between 100 and 300 K. This effect, combined with the sensitivity of the Au/sv/Au SVT to small changes in the hot-electron energy, more than compensates the reduction in the base transmission due to spin-wave scattering, leading to a net increase of the transfer ratio.

The results presented here show that the basic magnetotransport characteristics of the SVT depend on the emitter current or bias in a distinctly different way than for the MTT. When the emitter voltage of the MTT is increased by an amount ΔV_E, one increases the energy of the hot electrons that are injected into the base by the same amount ΔV_E. For typical transition metal ferromagnets (Co, NiFe, and CoFe), the spin asymmetry of the hot-electron attenuation length is reduced at higher hot-electron energy.[7,13] Therefore, the MC of a magnetic tunnel transistor is significantly reduced at high emitter voltage (current). In contrast, we have shown here that for the SVT the emitter current can be increased without significant changes in the hot-electron energy, such that the large MC is preserved. Thus, we have obtained spin-valve transistors with large magnetocurrent around 400% as well as high output collector current up to 40 μA.

ACKNOWLEDGMENTS

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