# SPIN-FILTERING OF NON-EQUILIBRIUM HOLES IN A SEMICONDUCTOR-FERROMAGNET HYBRID STRUCTURE

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Spin-dependent transmission of non-equilibrium electrons in ferromagnetic metals has been widely studied. The large spin asymmetry of the inelastic lifetime arises from the large difference in the number of empty states available above the Fermi level for the hot electrons to decay into. Experiments using spin-valve transistors, magnetic tunnel transistors and Ballistic Electron Emission Microscopy (BEEM) have yielded valuable insight into the factors that control spin-dependent hot-electron transmission. BEEM and its spin sensitive counterpart Ballistic Electron Magnetic Microscopy (BEMM) has also been used for magnetic imaging with nanoscale resolution.

Although spin-dependent transmission of hot electrons has been well addressed, the complementary spin-transport of non-equilibrium holes (below the Fermi level) has never been studied. Using a semiconductor/ferromagnet hybrid structure, we show here that a thin ferromagnetic film acts as an efficient spin-filter for holes. This has important implications not only in understanding several non-equilibrium phenomena, but also in realizing complementary building blocks for use in spintronics.

To investigate hole spin transport, Ballistic Hole Magnetic Microscopy (BHMM) has been developed. Here, the tip of an STM is positively biased such that unpolarized hot holes are injected into a ferromagnetic metal stack grown on top of a p-type Si semiconductor. A Schottky contact between Au and p-Si acts as the collector energy barrier for the transmitted holes. Hot hole transport with energies of 0.3 to 2 eV below the Fermi level has been studied for a p-Si/Au/Co stack with varying Co thickness. The hole attenuation length has been found to be short and increases from 6-10 Å in the energy range 0.8-2 eV. For a NiFe/Au/Co trilayer, the hole transmission is clearly spin dependent with a large magnetocurrent (MC) of 130%.

Alternatively, we have also demonstrated that reasonably large hole current can be collected when hot *electrons* are injected from the tip. In this reverse mode (R-BHMM), the hot injected electrons decay inelastically via electron-hole pair excitation, the holes of which are then transmitted through the ferromagnetic base and collected in the valence band of the semiconductor (see Fig.1, left panel). The hole current in this case also depends sensitively on the magnetic field (Fig.1, right panel). We observe a positive magnetocurrent of 180% at 1V. The origin of the spin-filtering of holes will be discussed using the electronic structure of ferromagnetic materials below the Fermi-level, suggesting that the transmission is largest for holes in the minority spin bands. This is confirmed by the experiments using reverse mode of BHMM. We suggest that in this mode, hot electrons of either spin create e-h pairs predominantly in the minority spin bands, followed by preferential transmission of holes in the minority spin bands in the second ferromagnetic layer. This explains the positive MC, and allows us to extract the hole attenuation lengths in NiFe for both of the spins.

Using the spin-filtering effect of hot holes, we have also demonstrated high-resolution magnetic imaging. Fig. 2 shows spatial maps of the collected hole current obtained by scanning the STM tip across a 2 micron square area of the sample at various magnetic fields. At large magnetic field the magnetic layers are in parallel magnetic alignment and a large hole current is observed. When the layers are aligned antiparallel, magnetic contrast appears and local regions of large hole current coexists with regions of reduced current. The magnetic resolution determined from this technique is found to be less than 30 nm.

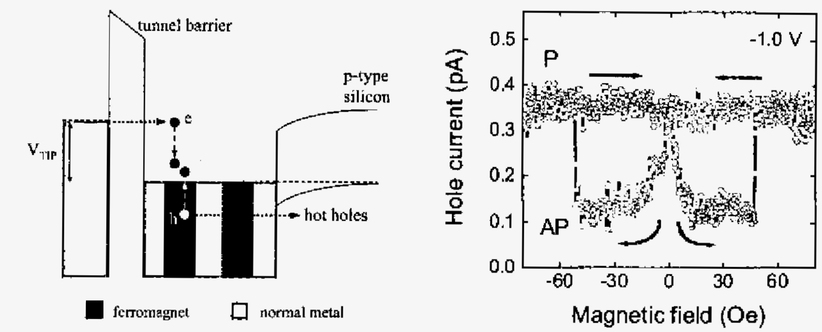


Fig 1. (left) Schematic energy diagram of ballistic hole magnetic microscopy in reverse mode. (right) Hole current versus magnetic field for p-Si/Au(7)/NiFe(1.8)/Au(7)/Co(1.8)/Au(3) for scattering mode of ballistic hole magnetic microscopy at −1.0 V and 4nA electron injection. MC=180%, T=150 K.

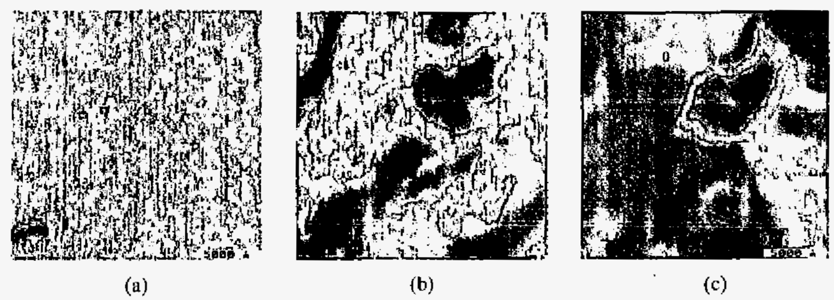


Fig. 2. BHMM ($2\times2\mu m^2$) images at various magnetic field of (a) +100 Oe, (b) −10 Oe, and (c) −23 Oe on a p-Si/Au(7)/NiFe(1.5)/Au(7)/Co(1.5)/Au(3) structure. Hole current is obtained in reverse mode at −1.6V and 3nA electron injection. The grey scale corresponds to a hole current of 0.5pA (dark) and 1.1 pA (bright). T=150K.