Ballistic Hole Emission Microscopy on Metal–Semiconductor Interfaces

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The transport of hot holes across metal–semiconductor interfaces is studied using ballistic hole emission microscopy. From the tip of a scanning tunneling microscope nonequilibrium holes are injected into a thin metallic overlayer on a p-type Si semiconductor, inducing a current of holes into the Si valence band. We have studied hole transport across interfaces between p-type Si and different metals (Au, Cu, and Al). It is found that the magnitude of the transmitted hole current depends strongly on the type of metal, the Schottky barrier height, and the energy distribution of the holes. In addition, we show that a significant yet smaller hole current can be induced in the reverse case where the tip is used to inject hot electrons, generating holes during inelastic decay in the metal overlayer. The results are compared to recent results on spin-dependent hole transmission in ferromagnet/p-type semiconductor structures.

***Index Terms*—Hot carriers, microscopy-ballistic hole emission, semiconductor-metal interfaces, spin dependent tunneling.**

I. Introduction

BALLISTIC electron emission microscopy (BEEM) [1] is widely used to study nanoscale properties of metal–semiconductor interfaces, ultrathin gate and tunnel oxides, and metallic and silicide thin films [2]–[4]. Its spin-sensitive counterpart, ballistic electron magnetic microscopy (BEMM) [5], can be used to probe buried interfaces in semiconductor-ferromagnet hybrid structures, employing the spin-dependent transmission of hot electrons in ferromagnetic thin films. The technique was demonstrated to allow magnetic imaging with nanoscale resolution [6].

Recently, spin-dependent transmission of hot holes, rather than electrons, was demonstrated in a p-type semiconductor-ferromagnet hybrid structure [7] using ballistic hole emission microscopy (BHEM). This opened up a new route for fundamental studies of spin dynamics of nonequilibrium carriers in ferromagnets and also for realizing complementary spintronic devices. In BHEM [8], [9] nonequilibrium carriers emitted from the tip of a scanning tunneling microscope (STM) are injected locally into a (ferromagnetic) metal overlayer on a p-type semiconductor as is shown in Fig. 1(a). The tip bias polarity is positive, such that a current of hot holes is injected by tunneling. Depending on the scattering in the metallic layers, a fraction of the hot holes is transmitted into the valence band of the semiconductor, provided the energy and momentum criteria for crossing the metal–semiconductor Schottky barrier are satisfied. In another recent work, large spin-dependent effects were also observed in the reverse mode of ballistic hole emission microscopy (R-BHEM) [10]. As shown in Fig. 1(b), in this reverse mode the tip voltage is negative, such that hot *electrons* are injected into the metal overlayer. During transmission of the metal stack, inelastic decay via electron–hole (e–h) pair excitation creates holes that can be collected in the valence band of the underlying p-type semiconductor. With this technique, magnetic imaging with nanometer resolution has been demonstrated [10]. Interestingly, it was found that the hole current induced by hot-electron injection in reverse mode is significantly *larger* than that obtained for the case of direct hole injection.

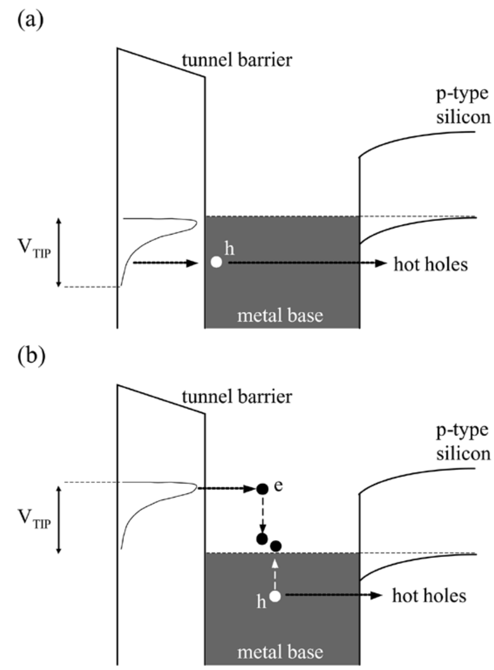

Fig. 1. (a) Schematic energy diagram of ballistic hole emission microscopy in direct mode (BHEM). A distribution of holes is injected by tunneling from a STM tip into a metal film on a p-type Si semiconductor. The transmitted holes are collected in the Si valence band. (b) Schematic energy diagram of ballistic hole emission microscopy in reverse mode (R-BHEM). The STM tip at opposite bias polarity is used to inject hot electrons. Inelastic scattering of the hot electrons in the metal base creates electron-hole (e-h) pairs, the holes of which can be collected in the valence band of the semiconductor.

In order to understand the spin-dependent transport of holes in these ferromagnet/semiconductor structures, it is important to examine the role of the Schottky barrier between the nonmagnetic metal and the p-type semiconductor collector. In this work we have studied the transport across metal/p-type Si(100) interfaces using various metals (Au, Cu, and Al). We compare the transmission of holes for these different interfaces for direct BHEM as well as for reverse mode (R-BHEM). We find that the transmission is significantly larger for lower Schottky barrier interfaces as a result of the energy distribution of the hot

Digital Object Identifier 10.1109/TMAG.2005.854738

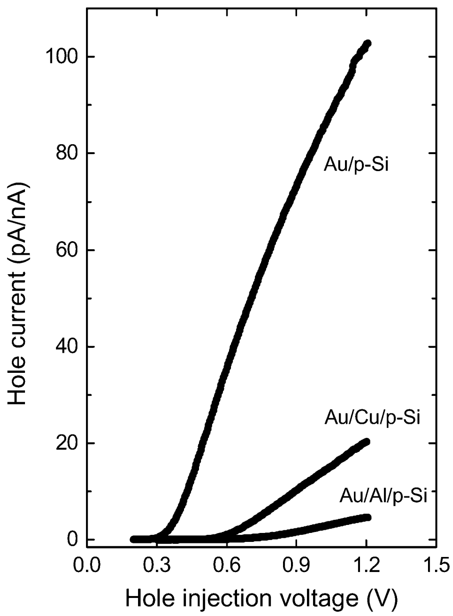

Fig. 2. Hole current per nA of injected holes versus positive tip voltage (BHEM mode) for Au(10 nm)/p-Si, Au(3 nm)/Cu(10 nm)/p-Si, and Au(3 nm)/Al(10 nm)/p-Si. $T = 150$ K.

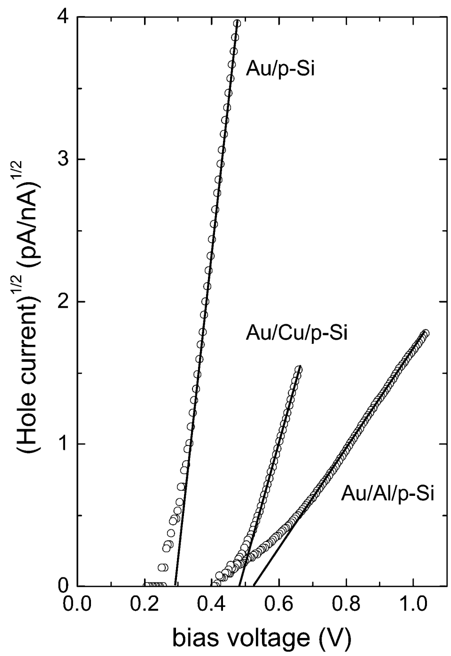

Fig. 3. Same data as in Fig. 2, but with the square root of the hole current plotted (symbols). The intercepts of the solid lines with the voltage axis correspond to the Schottky barrier heights.

holes. We also show that the hole current for the R-BHEM is consistently lower than for the direct hole injection, opposite to the case where the overlayer contains ferromagnetic metals as in [7] and [10].

II. Experimental Details

Samples used in this study are Au(30 Å)/metal/p-Si, where the metal layer is either 70 Å Au, or 100 Å Cu or Al. They were deposited by thermal evaporation in a molecular beam epitaxy system with a base pressure of 10^{-10} mbar. Substrates consist of HF-etched p-Si(100) with a lithographically defined area of 150 μm diameter, surrounded by a thick SiO_2 insulator. The Au cap layer of 30 Å is deposited to provide a chemically inert surface for *ex situ* sample transfer to the ultrahigh vacuum STM system with a base pressure of 10^{-10} mbar. BHEM measurements are performed at 150 K using PtIr tips, with the metal overlayer of the sample grounded. A contact to the back of the p-type Si is used to detect the hole current $I_{\rm hole}$ with a two-stage amplifier (10^{11} V/A) and a 300 Hz low-pass filter. Hole current spectra were recorded at several locations, and at least 15 spectra were averaged at each location. The spectra presented here therefore are representative of the whole surface. More details are described elsewhere [11]. The metal films are polycrystalline and have grain size and roughness comparable to that reported previously for structures grown on n-type Si [11].

III. Results and Discussion

Representative hole spectra for Au(30 Å)/metal/p-Si structures are shown in Fig. 2, obtained by sweeping the tip bias while recording the hole current $(I_{\rm hole})$ at a constant injection current of $I_T = 1$ nA. The sign of $I_{\rm hole}$ corresponds to holes flowing from the metal stack into the semiconductor back contact. For Au/p-Si, a rather sharp onset of the transmitted hole current is observed around 0.3 eV, corresponding to the Schottky barrier height Φ_b of the Au/p-Si interface. For the case of Au/Cu/p-Si, the transmitted hole current is smaller by a factor of five as compared to Au. The onset of $I_{\rm hole}$ occurs at a higher bias due to the different value of Φ_b for Cu/p-Si. The hole transmission for the Au/Al/p-Si structure is further reduced by a factor of five as compared to that of Cu. The Schottky barrier heights can be extracted by plotting the square root of $I_{\rm hole}$ as a function of the injection bias V (see Fig. 3), since near the threshold the current is expected to vary as $(V - \Phi_b)^2$. The intercepts of the solid lines with the voltage axis then correspond to the Schottky barrier height. For the Au, Cu, and Al we find Φ_b is 0.29 ± 0.03 eV, 0.48 ± 0.03 eV, and 0.52 ± 0.03 eV, respectively.

The hole transmission of 10% at $+1.2$ V for Au is rather large, despite the fact that the energy distribution of the holes injected by tunneling is peaked near the fermi level of the metal base film (see Fig. 1(a) and [8], [9]). Thus, a significant fraction of the injected holes do not have sufficient energy to overcome the Schottky barrier, even if no scattering occurs. The large $I_{\rm hole}$ indicates highly ballistic transport of the holes into the zone-centered Si valence bands and suggests a long inelastic lifetime of hot holes in Au, in agreement with recent calculations [12]. For Cu, the calculated inelastic lifetime is long, [12] just as in Au. Therefore, inelastic decay of the holes in the Cu film cannot explain the factor of five lower $I_{\rm hole}$ for the sample with Cu. We therefore attribute the difference to the value of Φ_b, which for Cu is much larger than for Au. Given the energy distribution of the holes injected by tunneling, a smaller transmission is expected for higher Φ_b since the hole current arises mostly from the tail of the energy distribution. This accounts for most of the difference, although some scattering at the additional Au/Cu interface may also contribute. However, we note that Au/Cu interfaces are expected to be rather transparent since the bandstructure of Au and

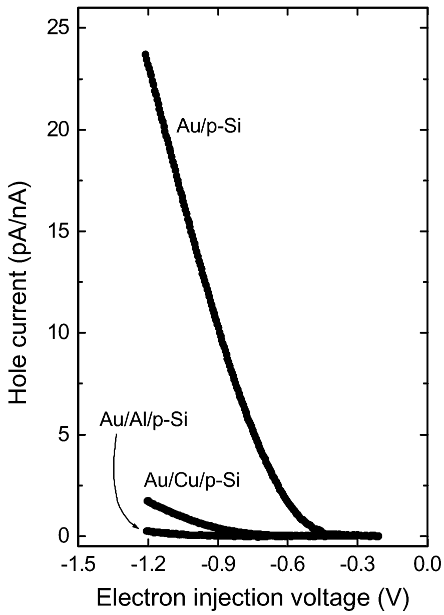

Fig. 4. Hole current per nA of injected electrons versus negative tip voltage (R-BHEM mode) for the same three samples as in Fig. 2. $T = 150$ K.

TABLE I
HOLE CURRENT FOR DIRECT AND REVERSE BHEM AND SCHOTTKY BARRIER HEIGHT Φ_b FOR DIFFERENT METAL/P-SILICON CONTACTS

structure	BHEM current at 1.2 V (pA/nA)	R-BHEM current at -1.2 V (pA/nA)	Φ_b (eV)
Au/p-Si	102	23	0.29
Au/Cu/p-Si	20	1.8	0.48
Au/Al/p-Si	4.3	0.2	0.52

Cu is quite similar in the relevant energy range. For the structure with Al, the Schottky barrier is only slightly higher than for sample with Cu. This, therefore, cannot account for the much lower hole current for the Al sample. Since the bandstructure of Au and Al are quite different, the hole transmision of a Au/Al interface is expected to be smaller than that of a Au/Cu interface. Moreover, during transport of the Al film the hole current is expected to be more strongly attenuated, since the calculated lifetimes of hot holes in Al are smaller than in noble metals such as Au and Cu [13].

In Fig. 4, we show spectra for the same structures as in Fig. 2, but obtained in reverse mode (R-BHEM) using negative tip bias, producing injection of hot electrons. The sign of the collected current is the same as for the direct BHEM case, proving the collection of holes. We again observe that I_{hole} is largest for the Au film, and smallest for the Al film. However, the reduction in current when going from Au to Cu to Al is more strong, about a factor of 10 in each step, as can be seen in Table I where the transmission results for direct BHEM and reverse BHEM are summarized.

Comparing the hole current for direct BHEM and reverse BHEM, we find that the latter is smaller for all the structures studied. Two factors are responsible. The hot holes created by the inelastic decay of the injected hot electrons have a more isotropic momentum distribution than holes injected by tunneling, which produces a more forward focused momentum distribution. In addition, the energy distribution of the holes created by the inelastic decay of electrons via electron–hole (e–h) pair excitation is different from the energy distribution of holes injected by tunneling. A similar trend was also observed in [8], [9] for Au on p-type Si. This is opposite to the case where the overlayer contains ferromagnetic metals as in [7] and [10], where a larger hole current was observed in the R-BHEM case.

IV. CONCLUSION

The transport of hot holes across metal/p-Si(100) interfaces has been studied using ballistic hole emission microscopy for both direct and reverse mode. We find that the magnitude of the collected hole current depends strongly on the type of metal, the Schottky barrier height, and the energy distribution of the holes, with consistently smaller hole current for the reverse mode.

ACKNOWLEDGMENT

This work was supported by the Dutch Foundation for Fundamental Research on Matter (FOM), the Royal Netherlands Academy of Arts and Sciences (KNAW), and the Dutch Technology Foundation (STW).

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Manuscript received February 7, 2005.