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A ballistic electron emission microscopy study of ferromagnetic thin films embedded in Au/GaAs(100)

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Abstract

A ballistic electron emission microscopy facility has been used to investigate hot electron transport through Au/M/Au and Au/M thin films (M = Fe, Co) grown on GaAs(100) substrates. The hot electron attenuation through the Au/Fe/Au trilayer roughly exhibited an exponential relationship with Fe interlayer thickness. Two values of Fe thickness (0.4 and 0.85 nm) were used to compare the differences between Fe embedded at the centre of the Au layer and Fe at the metal–semiconductor interface. For the thicker Fe layer, there is a large difference in terms of the transmitted ballistic electrons between the two structures, with the 'at-interface' structure exhibiting substantially increased transmission. This difference was not found in the Au/Co system with comparable Co thickness. The results suggest that the behaviour of transmitted hot electrons is dominated by the formation of the continuous metal layers with strong scattering at the metal–metal interfaces.

1. Introduction

The properties of metal–semiconductor systems, particularly the structures consisting of magnetic metal layers/multilayers on semiconductors, have been of interest [1] for a number of years. The study of their electron transport properties has been one of the active areas of research. Ballistic electron emission microscopy (BEEM) [2], developed from scanning tunnelling microscopy (STM), is capable of investigating both spatial-resolved imaging and electron transport properties at buried interfaces.

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As a three-terminal modification of STM, BEEM is a powerful method for the study of transport properties of those electrons, especially with energies from about 1 eV above the Fermi level in the metal, generally referred to as hot electrons. In a BEEM experiment, a tunnelling tip is positioned close to the surface of a metal–semiconductor sample. Electrons tunnelling from the tip to the metal base electrode typically have an attenuation length greater than 10 nm [3]. Provided that the thickness of the metallic layer is not much larger than the attenuation length, many electrons may ballistically traverse through the metal layer and reach the metal–semiconductor interface. Provided, also, a tip-base bias voltage V is larger than V_B, where eV_B denotes the Schottky barrier height of the metal–semiconductor interface, those hot electrons can enter the semiconductor collector electrode and result in a BEEM current, I_c, flowing from the base to the collector.

The BEEM study of Au layers grown on GaAs substrates has been performed by several groups [4–6]. It was also found that Au/Fe/Au trilayers and Au/Fe multilayers [7–9] deposited on various substrates exhibited giant magnetoresistance of about 15–20%. Kinno *et al* [10] also investigated the effect of an external magnetic field on the BEEM current through an Fe/Au/Fe trilayer grown on n-type Si(100). Under an applied magnetic field, the BEEM current I_c demonstrated hysteresis corresponding to that of the magnetization. In this paper, we first report a systematic BEEM study of Fe layers embedded at the centre of Au layers ('trilayer samples') with respect to various Fe thicknesses. Secondly, a comparison between trilayer samples and Fe layers located at the Au–GaAs interface ('bilayer samples') is presented with two chosen Fe thicknesses. The purpose is to investigate the relationship between hot electron transport properties and various interfaces of the system. For further comparison, preliminary results of the effects of Co layers of same thicknesses in place of the Fe layers have been also included in this paper.

2. Experimental details

Thin metal films were manufactured in a VG 80 M molecular beam epitaxy (MBE) chamber with a base pressure at 1.1×10^{-11} mbar. The substrates were GaAs(100) consisting of a 0.3 μm undoped epilayer on Si-doped, $n^+ = 2 \times 10^{18}$ cm^{-3}, substrates, capped with an amorphous arsenic layer. The substrates were first thermally decapped under a pressure of the order of 10^{-11} mbar, followed by cooling to 50 °C. Reflection high-energy electron diffraction (RHEED) measurements were performed to monitor the substrate surface reconstructions.

All the samples were decapped at a nominal temperature of 450 °C, at which an As-rich c(2 × 8) reconstruction was obtained. Au/M bilayers and Au/M/Au trilayers (M = Fe, Co) were deposited at typical growth rates of 0.01–0.02 nm s^{-1}. It should be noted that the shape of metal films deposited on semiconductor substrates may affect the low bias current–voltage characteristics [11, 12]. For instance, sharp corners on the perimeter of the films may result in comparatively high electric fields locally and an apparent increase in 'leakage current' at lower bias. Also, Prietsch [3] demonstrated that a small metal–semiconductor contact area is required in order to keep the BEEM current noise at a low level. In our work, a Ta mask was used to deposit a number of circular dots of diameter about 1 mm.

In trilayer samples, the top and bottom Au layers, serving to avoid oxidation of the Fe layer and act as a buffer layer, respectively, were nominally of the same thickness typically totalling 6 nm. The total Au thicknesses were kept the same as that of the Au overlayers in the bilayer samples. The total thickness of the dots was further measured by low-angle x-ray diffraction (XRD) and a commercial simulation program was used to evaluate the thickness and the roughness of both the Au and Fe layers. Prior to the BEEM measurements at room temperature, a thin InGa eutectic alloy was evenly applied to the rear faces of the semiconductor

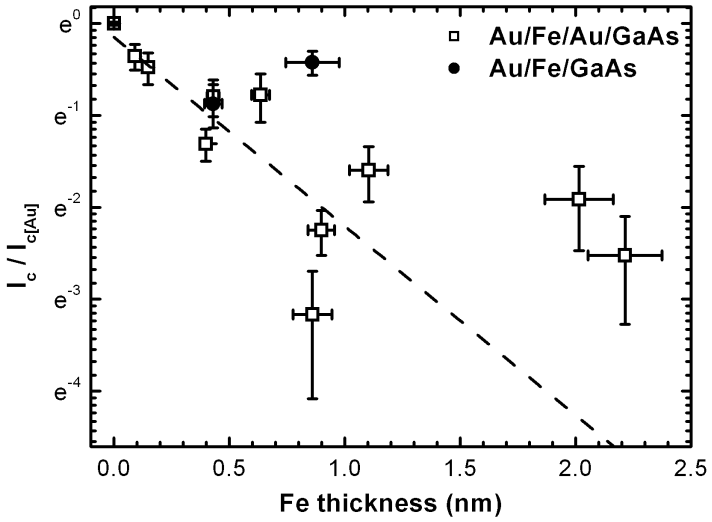

Figure 1. The attenuation of the normalized BEEM currents, $I_c/I_{c[Au]}$, as a function of the thickness of iron at a bias of 1.5 V for trilayer structures (open squares). The dashed line is an exponential fit to the data of the samples with Fe layer thinner than 0.5 nm. The normalized BEEM currents of the Au/Fe bi-layer samples, with Fe thickness of 0.4 and 0.85 nm, are also presented (filled circles). $I_{c[Au]}$ is the BEEM current of a Au layer on the GaAs(100) substrate with a Au thickness comparable to that of a trilayer or bi-layer structure.

substrates to create ohmic contacts. Limited by the mechanical stability of our STM setup, the spatial resolution of the BEEM work was estimated to be of the order of 10 nm. Our present work is focused on the averaged behaviour of the ballistic electrons. As such, numerous bias dependence spectra were taken at different locations of the sample surfaces and averaged results were then obtained. Therefore the thermal drift of the setup was not expected to have significant influence on our results. To ensure reproducibility, for the two chosen values of Fe thickness at least two samples grown under nominally identical conditions, each having a number of circular dots, were examined for each individual structure.

3. Results and discussion, (a): Au–Fe system

Firstly, the attenuation of BEEM currents of trilayer samples as a function of the thickness (0–2.2 nm) of Fe is shown in figure 1 at a bias of 1.5 V. The data are normalized to the experimentally measured BEEM current, $I_{c[Au]}$, of a Au layer grown directly on GaAs(100) with comparable Au thickness. This is to highlight the overall effects of introducing the Fe interlayer. The dashed line is a fit to an exponential decay of the normalized BEEM current for Fe thickness less than 0.5 nm. It is shown that the presence of the Fe layers dramatically reduced the BEEM current. The decrease is more than 50% for an Fe layer of only 0.4 nm and the trend of the attenuation is roughly exponential at this stage. The exponential dependence can be understood in terms of the increase of scattering cross-section as the Fe clusters occupy larger areas at the interface with increasing Fe deposition. When the Fe layer becomes thicker ($>\sim$1 nm), the attenuation of the BEEM current is slower and almost independent of the increase of Fe layer thickness. This implies that the initial dramatic decrease of the BEEM current with Fe thickness precedes the formation of a continuous Fe film, but that Fe thickness becomes less important for the hot electron transport behaviour in the thicker interlayer region,

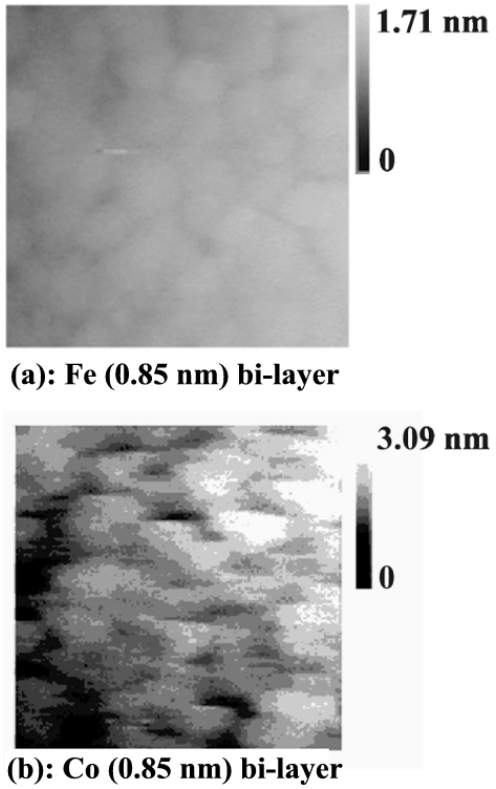

Figure 2. 200×200 nm^2 STM images of the Au (6 nm)/M (0.85 nm) bilayers, M = Fe, Co.

where fully two-dimensional metal layers are well represented. It should also be noted that the points between the Fe thickness of 0.4 and 0.8 nm were scattered, coinciding with the crucial stage of forming continuous Fe layers and this will be discussed later in this section.

Two values of Fe thickness (0.4 and 0.85 nm) were used to compare the difference between trilayer and bilayers samples. The surface conditions of all samples were monitored by STM, where the bias and tunnelling current were 1.0 V and 1.0 nA, respectively. A typical image of the 0.85 nm bilayer sample is shown in figure 2(a). Au clusters were observed with typical lateral sizes of 20–40 nm and thickness varying by 1.7 nm. Slightly rougher Au surfaces were found in both the trilayer and the 0.4 nm bilayer samples. This may reflect rougher morphology of thinner Fe layers for the bilayer samples and all trilayer samples. Based on an improved Bell–Kaiser model [3], the curve fit of BEEM current as a function of the bias of Au–Fe bilayers gives Schottky barrier heights of 0.82 ± 0.01 and 0.81 ± 0.02 eV for the 0.85 and 0.4 nm sample, respectively. By contrast, the Schottky barrier height is determined to be 0.86 ± 0.01 eV for the trilayer sample with 0.85 nm-thick Fe interlayer. These results are broadly in line with the fact that a well formed Au/GaAs Schottky barrier exists in the trilayer structures, whilst the Fe/GaAs Schottky barrier, which has a slight lower value, dominates the bilayer structures.

A comparison of the BEEM currents of Au–Fe trilayer and bilayer samples at several discreet bias voltages is presented in figure 3. The difference in magnitude of normalized BEEM currents at a bias of 1.5 V between the two cases is also presented in figure 1, along with the I_c attenuation data of trilayer samples. The BEEM current increased substantially

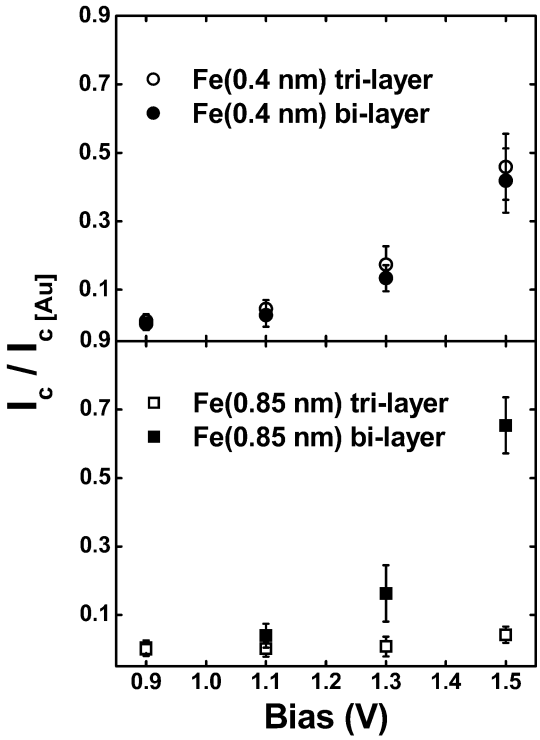

Figure 3. The normalized BEEM currents, $I_c / I_{c[Au]}$ at several bias values (0.9, 1.1, 1.3, and 1.5 V) of the Au–Fe bilayer and trilayer samples grown on GaAs(100) substrates. The thickness of the layers Fe is either 0.4 or 0.85 nm.

when the Fe layer of 0.85 nm was deposited directly on the GaAs substrates (bilayer) rather than sandwiched between Au layers. Nevertheless, for the thinner Fe layer (0.4 nm), the difference in BEEM current between bilayer and trilayer was negligible.

It has been shown [13] that at room temperature Fe layers on GaAs(100) substrates firstly grow as three-dimensional islands, followed by a gradual smoothing of the films at about five monolayers (∼0.71 nm). In another study [14], Gester *et al* managed to grow Fe layers and islands simultaneously until both of them started to coalesce at the stage of more than three monolayers (∼0.43 nm). In our work, when the thickness reached 0.4 nm, Fe had formed mainly separated islands. However the lower Schottky barrier of the Fe/GaAs contact led to its dominance at the interface. When the thickness of Fe was doubled, Fe of the bilayer sample was more likely to form a fully coalesced two-dimensional layer, resulting in much less scattering of hot electrons at the now better defined metal–semiconductor interfaces. Neglecting coherent processes, the relatively rough interfaces are likely to be one of the main sources of scattering to the hot electrons. Having one less Au–Fe interface, the enhancement of I_c was not unexpected for the 0.85 nm bilayer structure. We note that the study on highly ordered epitaxial system of $CoSi_2$/Si reported by Sirringhaus and co-workers illustrated also a bias dependence in the BEEM currents due to a coherent process of the electrons [15–17]. In contrast, the lack of such coherent process in our systems is indicative a much poorer interface quality for these structures on GaAs. As supported by previous BEEM measurements and related Monte Carlo simulation [18], for the systems with relatively rough interfaces, it is reasonable to assume that BEEM behaviour is mainly attributable to the scattering at both

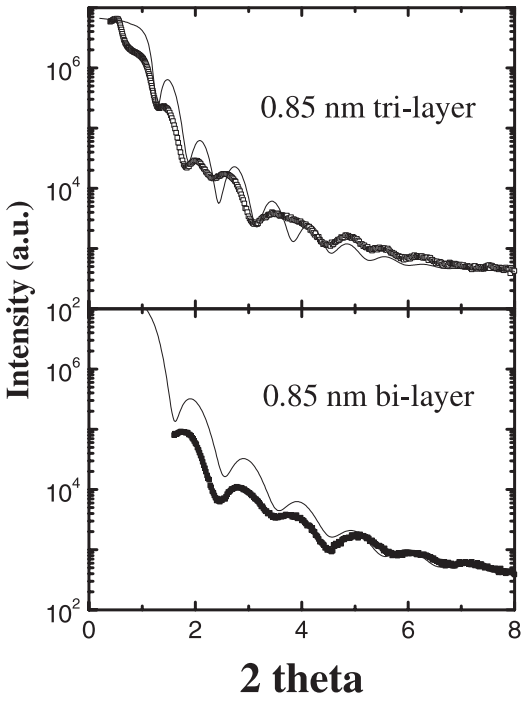

Figure 4. The low-angle, between 0° and 8°, XRD of a pair of Au–Fe tri- (upper curves) and bilayer (lower curves) samples with computer simulation (thin solid curves). The total thickness of Fe is 0.85 nm in both cases.

metal–semiconductor and metal–metal interfaces associated with the transition from three-dimensional islands to two-dimensional layers. Figure 4 shows the low angle XRD results of a typical pair of 0.85 nm Au–Fe tri- and bilayer samples. The solid curves in figure 4 are computer simulations. In order to achieve the best fitting, it is found that the roughness parameter of the trilayer samples must be more than twice as large as that of the bilayer samples.

4. Results and discussion, (b): Au–Co system

For purposes of comparison, both STM images and BEEM currents between Au/Co trilayer and bilayer structures deposited on GaAs(100) substrates at the equivalent experimental conditions have been carried out. The nominal thicknesses of both Co and Au layers were set to be comparable to the samples of the Au–Fe system. The STM image, shown in figure 2(b), exhibits more blurred contours and a larger thickness variation (∼3 nm) than the Au–Fe system. There are also major differences in their BEEM behaviour. Interestingly, no BEEM signal was detected in the case of the 0.4 nm Au–Co bilayer sample. In the $I_c/I_{c[Au]}$ measurements of the 0.85 nm samples, the bilayer sample showed similar values compared to its trilayer counterpart rather than any remarkable increase (figure 5).

As discussed in the previous section, as well as the scattering at both metal–semiconductor and metal–metal interfaces the formation of continuous metal coverlayers determines the hot electron transport properties. The morphology and magnetic properties of thin Co films are similar to those of Fe [19–21], but there are important quantitative differences. In recent work [21, 22], a full scenario of Co growth on GaAs(100) was given, with consideration of

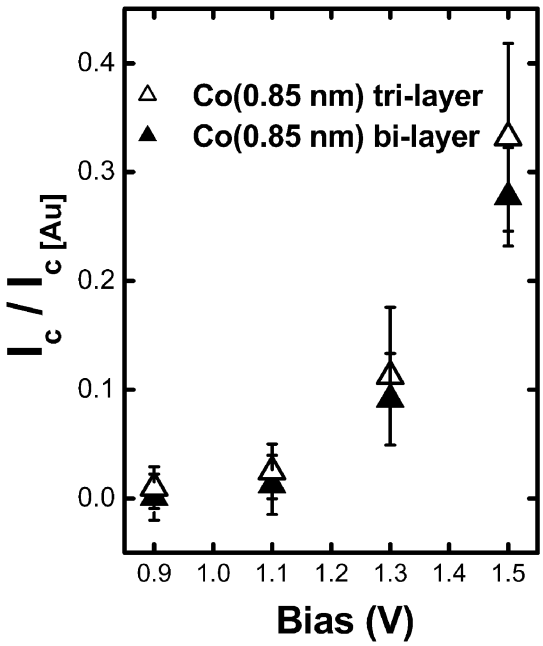

Figure 5. The normalized BEEM currents, $I_c/I_{c[Au]}$, at several bias values (0.9, 1.1, 1.3, and 1.5 V) for the Au–Co bilayer and trilayer samples grown on GaAs(100) substrates. The thickness of the Co layers is 0.85 nm.

all possible structures of Co overlayers. The results showed that the two-dimensional single crystalline structure, which was characterized by a well-ordered RHEED pattern, appeared only beyond a critical thickness of 1.5 nm. Compared to the critical thickness of Fe layers grown on GaAs(100) substrates, Co layers give rise to a later threshold of two-dimensional growth on GaAs(100). In contrast to the results in the Au/Fe samples, the two 0.85 nm Au/Co specimens exhibit similar magnitudes of BEEM currents.

Finally, it should be noted that the poor island-shape contact between very thin Co layers ($\sim$0.4 nm) and GaAs substrates might result in much stronger scattering of hot electrons at the metal–semiconductor interface. Consequently, the BEEM current of the 0.4 nm Au–Co bilayer sample was undetectable in our measurements.

5. Conclusions

The hot electron transport properties of Fe and Co layers embedded in the Au/GaAs(100) structure were investigated by a BEEM facility. Monitored by STM, the surfaces of all samples were reasonably smooth and exhibited no qualitative variation. Nevertheless, the BEEM currents between the Au–Fe bilayer and trilayer samples were very different. The Au/Fe (0.85 nm) bilayer sample exhibited a clear enhancement of the BEEM current compared to that of its trilayer counterpart, whereas no substantial difference in BEEM current was found when the thickness of Fe layer was only 0.4 nm. When Fe layers were substituted by Co, the BEEM currents did not show such variation. It is proposed that the BEEM measurement indicated a substantial improvement in the two-dimensional coalescence of Fe layers between 0.4 and 0.85 nm thicknesses. However, Co layers of the same thickness remained at an island

stage of growth. The whole process was closely related to the formation of continuous metal overlayers and the associated scattering processes at both metal–semiconductor and metal–metal interfaces. Further work is underway to investigate the effect with thicker layers of the magnetic metals.

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