# Enhanced Energy Resolution in Ballistic Electron Emission Microscopy Through InAs Base Layers

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Ballistic Electron Emission Spectroscopy (BEES) and Ballistic Electron Emission Microscopy (BEEM) offer the unique possibility of probing subsurface quantum states. To improve the spectroscopic sensitivity, it is important to increase the amount of electrons which are able to penetrate into the sample. In this work we show that the transmission coefficient and the attenuation length of the base layer can be enhanced by more than one order of magnitude, if the commonly used thin metal film is replaced by a molecular beam epitaxy (MBE) grown InAs layer. At low temperatures (T = 100 K), a passivated InAs layer yields an attenuation length in the order of 70 nm – 90 nm instead of 5 nm obtained on Au films.

During the last years, scanning tunneling microscopy (STM) and related techniques have evolved as powerful tools in the investigation of surfaces [1], [2]. With the introduction of ballistic electron emission microscopy/spectroscopy by Kaiser and Bell [3], [4] the unique spatial resolution of the STM has been combined with the possibility of local probing the electronic structure of sub-surface interfaces.

In typical BEEM experiments, the ballistic electron current is in the low pA range and thus, the transmission coefficient though the metal base becomes a limiting factor for spectroscopic resolution. If buried structures, such as minibands in superlattices, shall be investigated [5], the ballistic electron current through the superlattice will be smaller by at least one order of magnitude than e.g. for an Au-GaAs Schottky diode. In this work, low temperature BEEM studies are carried out on MBE grown InAs-GaAs heterostructures, where a degenerately n-doped InAs layer replaces the commonly used metallic base. At appropriate growth temperatures (550 °C) a closed and suitable flat InAs layer was achieved. Due to the large lattice mismatch between InAs and GaAs (7.2 %), such layers are strained, but as shown by Ke and coworkers [8] the strain is fully relaxed by dislocations for film thickness above 33 monolayers. InAs carries the unique advantage of a surface accumulation layer. For this reason, insulating surface depletion barriers like on other semiconductors such as GaAs or silicon do not play a role.

InAs-GaAs heterostructures with InAs film thickness between 160 nm and 300 nm were investigated. Bar-shaped InAs mesas (0.3 mm x 2.5 mm) were defined by photolithography and using a wet chemical etchant. Then, a In-Sn back contact was alloyed in forming gas atmosphere. A second etch process was made to obtain different InAs film thickness, followed by a polishing and passivation process based on an aqueous $P_2S_5/(NH_4)_2S$ solution originally introduced for GaAs [6]. Finally, an In-coated Au-wire was attached to establish an ohmic contact to the InAs layer. More details on this passivation process will be published elsewhere [11]. At room temperature, the internal resistance of the InAs samples was too low for reliable BEEM current detection and thus the STM head was put into a cryostat and slowly cooled to lower temperatures. For the present experiment, a temperature of T = 100 K was chosen, since this provides convenient STM operation conditions. All experiments were performed using Au tips and a tunnel current of $I_T$ = 1 nA at a initial bias voltage $V_{Bias}$ = 2 V. The electronic circuitry for measuring the BEEM current is described in [7].

In contrast to the data of Au-GaAs reference samples, two onset voltages are clearly visible in typical BEEM spectra. The lower onset voltage in Fig. 1(a), $V_b$ = 0.65 V, is the threshold voltage for ballistic electrons overcoming the barrier at the InAs-GaAs interface in the Γ-valley. Using BEEM, Ke and coworkers [8], [9] have studied the properties of InAs-GaAs heterojunctions as a function of the InAs thickness, however, still with an Au-base layer on top. They found that the barrier height at the InAs-GaAs interface depends on the thickness of the InAs film and decreases non-linearly from 0.9 eV at a thickness of one monolayer to 0.63 eV at 33 monolayers. Above that thickness, a constant barrier height was obtained in their work indicating that the strain in the InAs film is fully relaxed. The onset voltage of $V_b$ = 0.65 V in our work is in excellent agreement with their data. The second threshold at higher bias, $V_L$ = 0.79 V, can be associated with the onset of ballistic electron transport through the L-valley of the InAs film. The L-valley of GaAs cannot be associated with the observed current onset at $V_L$, since it is much higher in energy in our samples. A third onset at somewhat higher bias voltages due to ballistic electron transfer into the L-valley of GaAs, however, could not be resolved in the present experiment.

To analyze the data in more detail, a modified Bell-Kaiser [4] model was applied. In addition to the original model, we also included electron transmission through Γ and L-valley of InAs, quantum mechanical reflection[10] at the GaAs-InAs barrier and a experimentally measured voltage dependent tip-sample separation [11]. For the InAs film, a bulk-like bandstructure was assumed. The effective masses in Γ and L valley were taken from [12]. Nonparabolicity effects were neglected since their influence on the calculation was found to be relatively small. Phonon assisted interface scattering is supposed to play a major role in our samples, and thus, the strict $k_{//}$ conservation rules were relaxed in our calculation. As we have included electron transmission through the Γ and L-valley of InAs in our model, the onset voltages $V_b$ and $V_L$ as well as the transmission factors through the Γ and L valley, $t_\Gamma$ (= 0.7 %) and $t_L$ (= 6 %), are obtained independently. Fig. 1(b) shows the transmission of an InAs film as a function of film thickness (T = 100 K). For reference purpose, the transmission of different Au-films (T = 300 K) is shown also. Note that the attenuation length of Au is almost independent of temperature and changes only in the order of 10 % between T = 300 K and T = 77 K (see Ventrice [13] e.g.). As one can see, the transmission of an Au-film is considerably smaller than the transmission of an InAs film. For the InAs film itself, the transmission through the L-valley is found to be 8.6 times larger than through the Γ-valley for all film thicknesses. From these data, the attenuation length of ballistic electrons, $\lambda_a$, can be determined. For this purpose, the ballistic electron current $I_{BEEM}$ is expressed as

$$I_{BEEM} = I_T t e^{-d/\lambda_a} \quad (1)$$

where $I_T$ is the tunneling current, t the transmission coefficient of the base layer obtained from the Bell-Kaiser model and d the film thickness. From this procedure, we obtain values of $\lambda_a$ = 4.6 nm for gold, 46 nm for the InAs Γ-valley and 70 nm for the InAs L-valley, respectively.

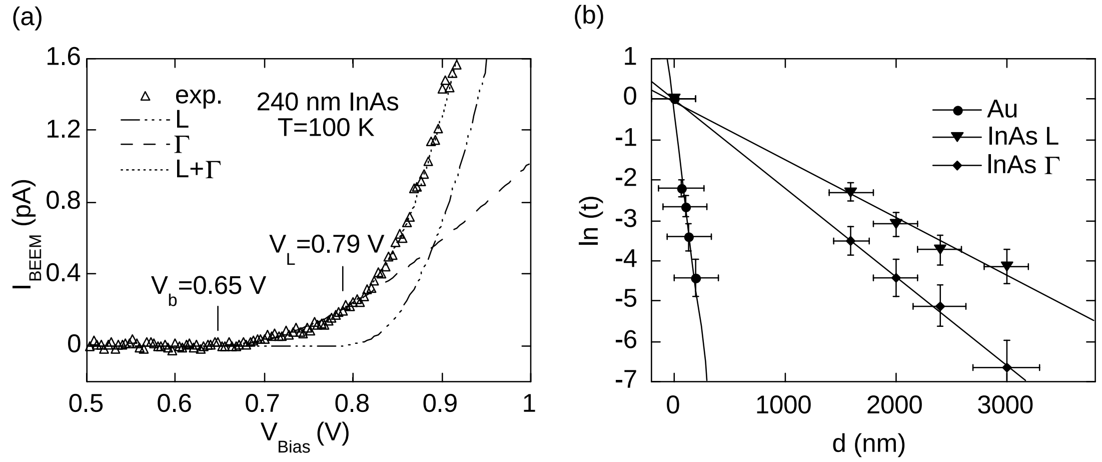


Fig. 1: (a) Representative BEEM spectrum for a 240 nm InAs layer. (b) Transmission coefficients for ballistic electrons through an Au-film (T = 300 K) and the Γ and L-valley of InAs (T = 100 K).

The attenuation lengths in InAs are approximately one order of magnitude larger than in Au and moreover, the attenuation length in the L-valley is approximately 30 % larger than for the Γ valley. For the Γ valley, the large attenuation length is qualitatively understood by low electron-electron scattering rates, due to the low carrier concentration in the InAs film compared to a metal film. The large transmission coefficient and the large attenuation length for electrons passing the L-valley of InAs, however, is somewhat surprising and needs a more detailed discussion. In our opinion, the process can be explained as follows: To be transmitted ballistically through the InAs L-valley, the electron has to undergo at least two scattering processes. First, the electron has to gain a large k-vector, necessary to enter the L-valley of InAs which is located at the boundary of the Brillouin zone in k-space. After the electron has reached the InAs-GaAs interface, a second scattering process is necessary to enable the transfer from the InAs L-valley into the Γ-valley of GaAs. Electron transfer into the L-valley of GaAs will only occur at higher energies and was not observed in the present experiment.

The second major advantage of InAs, or in general semiconductor base layers, results from the low effective mass. Due to the large electron mass difference in Au and GaAs, parallel momentum conservation leads to considerable electron refraction at the Au-GaAs interface. As a consequence, the energetic distribution of the ballistic electron current is inverted beyond the interface and the corresponding energetic resolution is considerably decreased. For InAs-GaAs heterostructures, however, this is not the case, since the effective mass in InAs is smaller than in GaAs. Consequently, the energetic distribution of the ballistic electron current is focussed beyond the InAs-GaAs interface and the energetic resolution of the measurement is enhanced.

In summary, we have performed BEEM studies on InAs-GaAs heterostructures, were the commonly used metal base was replaced by an degenerately doped InAs film. We have demonstrated that the BEEM current and the attenuation length of ballistic electrons is enhanced by approximately one order of magnitude on this samples. It is found that this enhancement is due to lower scattering rates in the Γ-valley of InAs and also to a large contribution of ballistic electrons passing the semiconductor base through the InAs L-valley. This enhancement of the BEEM current is beneficial for all applications, where the BEEM signal is expected to be small such as for the investigation of buried superlattices or self assembled quantum dots.

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