Hot electron transport in metallic spin valve and graphene-silicon devices at the nanoscale
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Chapter 2

Ballistic Electron Emission Microscopy and Related Techniques

Abstract

Development of the Scanning tunneling microscope (STM) has led to the remarkable progress in the field of surface characterization of conducting materials with atomic resolution. Beyond that, a modified version of this technique is used to hot electron transport and for microscopy studies in conducting thin films, known as Ballistic electron emission microscopy (BEEM). In addition to that, visualization of spin transport was also achieved using the magnetic version of BEEM by locally mapping the spin-dependent transport in spin valves. Although studies using hot electrons in solids were initiated in the past, it is only in later years that numerous progress have been achieved, concerning the nanoscale measurement of hot electron transmission in various thin films. In this chapter, the main concepts of hot electron transport and BEEM are presented. The chapter is based on published work in this field. We start with a brief introduction to the working principle of BEEM followed by an overview of BEEM and other techniques related to BEEM used in this research.

2.1 Introduction

Developed in the late 1980’s by Kaiser and Bell [1], Ballistic electron emission microscopy (BEEM) is considered to be a versatile technique which can probe both the energy and spatial dependence of transport of hot electrons in thin films. In BEEM, a Scanning tunneling microscope (STM) [2] is modified with an additional electrode to collect the hot electrons across a Schottky barrier. The main motivation of this chapter is to give an overview of the ballistic hot electron transport in solid state devices and then to discuss briefly the nanoscale technique i.e., ballistic electron emission microscopy (BEEM) and other related techniques derived from BEEM. An overview of the BEEM theory is presented with a discussion of the two most commonly used models namely, Bell-Kaiser (BK), and Ludeke-Prietsch (LP) model. The resolution of these techniques using few examples from published literature are described. Here, we have discussed the parts of BEEM technique which
Figure 2.1: A number of metal base unipolar hot-electron transistor devices. Out of these 3 device structures, the M/I/M/S is similar to our BEEM related experiments.

are directly relevant to our own experimental work whereas a more detailed review about BEEM can be found in Ref. [3, 4, 5]. This thesis includes results using BEEM, Ballistic hole emission microscopy (BHEM) [6, 7], Scattering (Reverse) BEEM and BHEM (RBEEM, RBHEM) [6, 8], and Ballistic electron/hole magnetic microscopy (BEMM/BHMM) [9, 10] which are presented in the later chapters.

2.2 Hot and Ballistic electrons

Hot electron phenomena have become important for the understanding of all modern semiconductor devices. Electrons having energies higher than a few tenths of one electron volt (eV) above the Fermi level of the system, are referred to as “hot” electrons. Electrons which contribute to the electrical conductivity in solids are free electrons with energies a few $k_B T$ (≈25 meV at 300 K) above or below the Fermi level. If we make a simple analogy of the electron energy to the real lattice temperature ($eV = k_B T$) then electrons of energy 1 eV above the Fermi level would correspond to a temperature rise up to $\approx 12000$ K [11]. However, those energies are not accessible simply by increasing the temperature of the material. Here we thus consider the kinetic energy (K.E.) of the hot electrons not the actual device temperature. In our research we focus on hot electron and hot hole transport through metallic multilayer, for energies in the range of 1 eV to 2 eV above (for electrons) and below (for holes) the Fermi level.

Above the Fermi energy, there are lots of unoccupied states for the hot electrons to occupy, in contrast to the thermal electrons where the energy levels are filled. Therefore the scattering mechanisms for hot electrons and electrons at Fermi level
are very different. According to Fermi’s golden rule, the electron should find an empty states to scatter into, which is very unlikely for the electrons at the Fermi level as all bands are filled as described by Fermi-Dirac distribution:

\[
F(E) = \frac{1}{1 + exp \left( \frac{E-E_F}{k_B T} \right)}
\]  

(2.1)

So, to have scattering into the empty states, the maximum interaction energy of electron is \(\approx 3k_B T = 78 \text{ meV}\). Hence elastic or quasi-elastic scattering are the dominating scattering processes at Fermi level, whereas inelastic electron-electron (e-e) scattering becomes more dominant at these higher energies. The inelastic scattering of hot electrons is caused by the Coulomb interaction with the other electrons below the Fermi-level which excite the electron above the Fermi-level and this process is called as Stoner excitation. Hot electrons loose a large part of their energy via this inelastic scattering event. Electron-phonon scattering is considered to be a quasi-elastic process, since hot electrons can suffer only an energy loss of the order of \(k_B T\), which is not significant compared to the initial electron energy. Defects and impurity scattering of electrons are always present in any metal and introduce a temperature and energy independent elastic scattering contribution [12]. However, if during the propagation through the metal base, the hot electrons stay unscattered between two scattering events, they are called “ballistic” electrons. In ideal situation ballistic hot electrons do not lose energy or undergo a change in momentum and form the major contribution to the collector current. Metal base ballistic hot electron transport can be realized in three different device structures as shown in the Fig. 2.1 and they are discussed in the next subsection.

### 2.2.1 Hot electron devices

Successful commercial utilization of hot-electron phenomena is a Gunn diode, based on the intervalley transfer mechanism for a negative differential resistance. A hot electron device using three electrodes in a triode configuration was first demonstrated by Mead in the year of 1961 [13]. Recently, semiconductor devices based on hot electron effects have made remarkable progress in the field of spintronics. In general a three-terminal transistor-like device can be fabricated for ballistic hot electron creation and detection in an all-solid-state structure as shown in Fig. 2.2a, b, and c. In these three terminal devices, hot electrons are injected by an emitter electrode through a Schottky or a tunnel barrier into a thin metallic base electrode. The base electrode is separated from the subsequent collector electrode by a similar potential barrier which acts as an energy filter. If the electron injection energy is higher than the base/collector barrier height and the base is thin enough so that a fraction
of the injected electrons can cross it ballistically, then those hot electrons are eligible to overcome the collector barrier and contribute to the collector current. Three of such device concepts are used: i) in spin valve transistor as in Fig. 2.2d, ii) for the investigation of spin transport in Si in Fig. 2.2e and iii) for the graphene-based hot electron transistor in Fig. 2.2f.

The concept of BEEM experiment is very similar to the M/I/M/S device configuration as shown in Fig. 2.2b. The most essential part of the BEEM device is the rectifying metal/semiconductor Schottky interface which is used as the energy filter of the hot charge carriers. In the next section, we thus discuss the basic theory of such rectifying M/S interface whereas the detailed understanding can be found in the textbooks [17, 18].

### 2.2.2 Rectifying metal/semiconductor (M/S) Schottky collector

When a M/S interface is formed there will be a flow of free carriers from one material to the other due to the mismatch in Fermi levels and a potential barrier will be established between the metal and semiconductor called as Schottky barrier. For a n-type semiconductor when a metal layer is deposited to make electrical contact
then there will be a flow of electrons from the n-type semiconductor to the metal. Since there is a net flow of charge carriers there will be an accumulation of electrons at the metal side and a space charge will build up between the two surfaces. This accumulation will grow until there is no more net charge carrier flow and a thermal equilibrium is established resulting in the lining up of both Fermi levels. Due to the space charge there will be an internal electric field across the M/S interface which will result in a potential difference between the metal and the semiconductor bulk called the contact potential. The carrier density in the metal is much higher than in the semiconductor, therefore the space charge region is much deeper in the doped semiconductor than in the metal. The width of the space charge layer in the semiconductor which is completely depleted of electrons is denoted by $W_d$. When the metal and semiconductor are in contact an equilibrium will be established as shown in Fig. 2.3a. The barrier height between the metal and the semiconductor without considering any interface states is then given as:

$$\phi_{B(n)} = \phi_m - \chi$$  \hspace{1cm} (2.2)

where $\phi_m$ is metal work function, $\chi$ is electron affinity of the semiconductor and thus $\phi_{B(n)}$ is completely determined by bulk material properties. This relation is called the Schottky-Mott relation. Similarly for a p-type semiconductor as shown in Fig. 2.3b, the barrier height will be:

$$\phi_{B(p)} = E_g - (\phi_m - \chi)$$  \hspace{1cm} (2.3)

where $E_g$ is the band gap of the semiconductor.
Thermionic emission theory
The electrical transport across the Schottky barrier is described by thermionic emission theory [17, 18]. It is assumed that the flux of electrons emitting from the surface is equal to the flux of electrons received on the surface. The flux of electrons arriving at the surface is defined as the number of electrons passing through a unit area per unit time and is given by:

\[ J = en \nu \]  
(2.4)

where \( e \) is the electrical charge of an electron, \( n \) is the electron concentration which is determined by Maxwell-Boltzmann statistics and \( \nu \) is the mean velocity of the electrons. Using this and subtracting the current which flows from the metal to the semiconductor \( J_{M \rightarrow S} \) from the current flowing from the semiconductor to the metal \( J_{S \rightarrow M} \) the following expression for the total current density \( J_n \) can be given:

\[ J_n = J_S \left[ \exp \left( \frac{eV}{k_B T} \right) - 1 \right], \quad \text{where} \quad J_S = A^* T^2 \exp \left( \frac{-e \phi_B}{k_B T} \right) \]  
(2.5)

where \( J_S \) is the saturation current density and \( A^* \) is the Richardson constant for thermionic emission of electrons from the semiconductor to the metal, \( V \) the voltage applied to the Schottky barrier and \( T \) the temperature. \( A^* \), which takes into account the effective mass, is defined as:

\[ A^* = \frac{4\pi m^*_e k_B^2}{\hbar^3}. \]  
(2.6)

Apart from the Richardson constant there are other effects which play a role in thermionic emission. These are the quantum mechanical transmission effect and electric-field-enhanced emission. The Richardson constant can be modified to account for these effects and is called the effective Richardson constant \( A^{**} \). Examples of the effective Richardsons constant are: \( A^{**} \approx 110 \) and \( 30 \, \text{A-cm}^{-2} \cdot \text{K}^{-2} \) for n-Si and p-Si respectively. The final equation describing the charge transport when thermionic emission is dominant becomes:

\[ J = J_S \left[ \exp \left( \frac{eV}{\eta k_B T} \right) - 1 \right] \approx J_S \left[ \exp \left( \frac{eV}{\eta k_B T} \right) \right] \quad \text{for} \quad eV \geq 3k_B T. \]  
(2.7)

Where \( J_S \) now uses the effective Richardson constant \( A^{**} \) and \( \eta \) is the ideality factor describing the deviation from the ideal situation. For \( \eta = 1 \), the current transport process is pure thermionic emission. However, thermionic emission is not the only process which scales exponentially with the applied voltage and then the diode can be non ideal with \( \eta > 1 \).

The Schottky barrier height, \( \phi_B \) can also be directly measured as an onset of the BEEM current and it should be comparable with the value obtained from such \( I-V \) measurement with \( \eta \approx 1 \).
2.3 Ballistic Electron Emission Microscopy (BEEM)

BEEM is a modified form of a scanning tunneling microscope (STM) allowing the nanoscale study of nonequilibrium carrier transport across buried interfaces. The difference from a normal STM setup is the addition of a back contact to the sample. This makes it possible to collect the injected electrons which have traveled through the complete device. The basic schematics of this is shown in Fig. 2.4. The current is injected perpendicular to the layer stack in a current-perpendicular-to-plane (CPP) geometry. The transport of the hot electrons can be divided into four different stages:

1. Injection of the charge carriers from the tip into the metal base,
2. Transport through the metal base,
3. Transmission across the M/S interface,
4. Transport through the semiconductor.

Charge carriers are injected from the tip by tunneling into unoccupied states of the thin metal base. This results in an angular and energy distribution of the injected carriers at the metal surface. After the injection, the hot charge carriers will propagate through the metal film. When the carriers reach the interface and satisfy the energy and momentum criteria at the interface, they can be transmitted through the M/S interface and enter the semiconductor. Finally, after transport across the semiconductor the electrons will be collected and form the BEEM current. Due to

Figure 2.4: The BEEM setup is visualized with the electrical circuit attached to it. A constant tunnel current $I_T$ is injected at variable tunnel voltages $V_T$. The injection and acceptance cones are visualized by the orange cones (⌀ ≈ 1 nm). Electrons which surpass the SB are detected as BEEM current $I_B$. 
2. Ballistic Electron Emission Microscopy and Related Techniques

2.3.1 Spectroscopy and imaging

The most widely used mode of the BEEM technique is the spectroscopy mode which provides information on local transport characteristics of hot electron between the STM tip and the semiconductor. The simplified energy band diagram of the BEEM experiment is shown in Fig. 2.5 together with the BEEM current with respect to the sample tip bias. The BEEM current consists of a small fraction of the injected electrons which satisfy the necessary energy and momentum criteria for collection across the M/S interface. No BEEM current will be observed when the tip bias is below the Schottky barrier height. By gradually increasing the tip bias, the BEEM current can be observed beyond a certain onset which corresponds to the Schottky barrier height. The higher the tip bias, more electron will contribute to the BEEM current. A BEEM spectra thus can be obtained by recording the BEEM current with respect to the tip bias at a fixed tip position. In general to improve the signal to noise ratio several BEEM spectra are recorded to obtain a single averaged spectrum. The final BEEM spectrum provides the information of energy dependence of hot electron transport in the metal film as well as the M/S interface. The onset of the BEEM spectra determines the Schottky barrier height with high accuracy (≈ 0.01 eV) whereas the spectral shape carries information about scattering in the metal film, across the M/S interface and in the semiconductor.

Figure 2.5: a) A schematic energy level diagram of a negatively biased tip with the hot electron distribution in red. Note that not all the electrons from this distribution have sufficient energy to pass the barrier. b) Typical BEEM spectrum, with the threshold value $V_0$, which corresponds to the Schottky-barrier height $\phi_B = eV_0$. 

the very local nature of injecting electrons and the requirement of lateral momentum conservation at the interface this technique results in a very high spatial resolution imaging.
2.3. Ballistic Electron Emission Microscopy (BEEM)

Figure 2.6: (a) STM topography and (b) simultaneously recorded forwarded BEEM current image at 77 K on epitaxial CoSi$_2$/n-Si(100) surface ($V_T=1.5$ V, $I_B=3$ nA, film thickness =3.8 nm). Two different surface reconstructions are apparent, and the BEEM contrast reflects the atomic scale periodicity of the surface topography. The BEEM contrast ranges from 25 pA (black) to 55 pA (white). Adapted from Ref. [20].

A direct spatial map of the BEEM transmission can be obtained by using the BEEM imaging mode. Using the capability of the STM tip to scan the conducting surface, the BEEM image can be mapped by simultaneous recording the BEEM current at a fixed tip bias above the threshold value. A comparison between the BEEM image and the surface image provides information about the transport characteristics with respect to the structural properties of the metal film and the M/S interface. Although it is not always very easy to interpret the lateral variation of the BEEM image, the possible reasons for inhomogeneous interface transmission are due to local variation in the metal layer thickness, variation in the local Schottky barrier heights, lateral variation in the interface bonding across the M/S interface etc. Such variation in BEEM current can be at a length scale of few Å as discussed latter.

Resolution of BEEM

Using the spatial variation of BEEM current it is possible to determine the resolution of the technique. An important feature of BEEM is that the resolution of BEEM imaging is not limited by the technique but by the structure of the sample being imaged. Lateral resolution of BEEM has been established by Miliken et al., [19] on a polycrystalline Au/Si(111) sample with SiO$_2$ patterns on top. From the sharp onset of the BEEM current in the absence of SiO$_2$, it has been shown that the resolution of BEEM is 10 Å. Even further, much better resolution has been demonstrated by Sirringhaus et al., [20] in an epitaxial system of CoSi$_2$/Si(100). Figure 2.6(a) shows atomically resolved CoSi$_2$ surface topography whereas Fig. 2.6(b) corresponds to the BEEM current variation also with atomic periodicity. In presence of surface point
defects like missing adatom as indicated by the arrow in the surface topography, local BEEM current increases which confirms BEEM has an atomic scale resolution.

2.4 BEEM Theory

In order to extract the Schottky barrier height from spectroscopy measurements a theoretical model is needed to fit the data. The first theoretical description dealing with the transport of hot-charge carriers through a metal-semiconductor system in a BEEM setup was proposed by Bell and Kaiser. As mentioned before, the transport of the charge carriers can be characterized into four different regions. The processes described in this chapter are for hot electrons due to the use of n-type silicon substrates and the theory is also valid simultaneously for hot holes.

2.4.1 Tunnel injection of non-equilibrium charge carriers

The applied potential between the tip and the metal base, called the tip voltage $V_T$, will determine the energy of the injected electrons. Tunneling across the potential barrier between the tip and the metal will always result in a distribution of the energy and momentum of the electrons. In common BEEM theory [1] the tunnel injection of non-equilibrium electrons from the tip into the base is assumed to behave according to the planar tunneling theory [21]. Although it has been shown that it is not always valid to use planar tunneling theory, the voltage spectroscopy measurements with BEEM are found to agree well with planar tunneling based theory [22]. At tip voltages close to the threshold results in a sharply peaked distribution of the injected electrons perpendicular to the M/S interface. Therefore the injected electrons will have little momentum parallel to the metal base ($k_\parallel \ll k_\perp$).

2.4.2 Transport across the metal base

Due to scattering, the spatial and energetic distribution of the electrons will broaden when traversing the metal base. The hot electron attenuation length can be described by a single parameter called the attenuation length $\lambda(E)$ which in principle is energy dependent. The attenuation can than be described by an exponentially decaying function depending on the injection angle $\theta$ away from the surface and metal film thickness $d$:

$$\frac{I_B(t,E)}{I_T} \propto \exp\left[\frac{-d \cdot \cos(\theta)}{\lambda(E)}\right]$$

(2.8)

Since the electrons are injected with almost zero parallel momentum $k_\parallel = 0$ we can assume $\cos(\theta) \approx 1$ simplifying the equation.
2.4. BEEM Theory

2.4.3 Scattering mechanisms

All of the different scattering processes which are relevant for our studies in this thesis occur in the metal base. In Fig. 2.7 the most prominent scattering mechanisms are depicted, which are:

**Ballistic transport** Ballistic transport is the unscattered propagation of electrons through the metal base. If the electrons travel ballistically through the metal base they might have enough energy, depending on $V_T$, to surmount the Schottky barrier at the M/S interface.

**Inelastic scattering** If the electrons are scattered inelastically their energy will be reduced. The processes dominating this form of scattering, at the energies is electron-electron (e-e) scattering [6] and will typically result in a reduction of half the electron energy. At low tip voltage this effectively means that any inelastically scattered electron will not have enough energy to surmount the Schottky barrier. However at higher tip voltages, at least at an energy twice that of the Schottky barrier, the collision might result in a secondary electron with enough energy to surmount the Schottky barrier along with the primary electron that still has an energy above the Schottky barrier, thereby increasing the BEEM current. Although phonon scattering...
can also result in energy loss they are not taken into account since the change in energy is negligible small, on the order of $k_B T$, in comparison with e-e scattering.

**Elastic scattering** This form of scattering will change the momentum but conserve the total kinetic energy of the electrons. Therefore any elastic scattering will result in a broadening of the distribution of angular momentum. Since transmission across the M/S interface is sensitive on the momentum, as shown in section 2.4.5, elastic scattering will also have an effect on the BEEM current. Grain boundaries, impurities, defects and any inhomogeneities in general are the main elastic scattering sites.

**Impact ionization** When an electron with high enough energy enters the semiconductor it could transfer a part of its energy to an electron in the valence band. If enough energy is transfered it could excite the electron to the valence band creating an electron-hole pair. This electron could then contribute to the BEEM current. For this however the impacting electron should have an excess energy above the threshold of more than twice of the semiconductor band gap. Since all experiments are performed below this limit, impact ionization is not present.

### 2.4.4 Electron attenuation length

With increasing metal base thickness the BEEM current is attenuated. The total attenuation length, $\lambda$ is related to the inelastic attenuation length, $\lambda_i$ and the elastic attenuation length, $\lambda_e$ as described by Matthiessen’s rule:

$$\frac{1}{\lambda(E)} = \frac{1}{\lambda_e} + \frac{1}{\lambda_i(E)} \quad (2.9)$$

From equation 2.8 it is clear that the transmission exponentially depends on the film thickness of the metal base. Therefore, by varying the metal base layer thickness and measuring the transmission at a particular energy a plot can be obtained of the transmission versus metal base thickness and energy. Using an exponential axis for the transmission, the slope of the plot gives the electron attenuation length at a particular energy. The energy dependence of the attenuation length can now be obtained by repeating this process at different energies. By BEEM $\lambda_e$ and $\lambda_i(E)$ can not be measured directly. However, the inelastic attenuation length is energy dependent and proportional to the product of the group velocity and the inelastic electron lifetime. Using Fermi liquid theory the energy dependent inelastic scattering can be described as: $\lambda_i(E) \propto (E + E_F)^{0.5}/E^2$, $E_F$ is the Fermi energy of the metal. Although there are possibilities to extract the two different attenuation lengths $\lambda_i$ and $\lambda_e$ from $\lambda$ but this is generally not so straight forward.
2.4.5 Transmission across the M/S interface

The transmission across the barrier is dependent on the energy and the momentum of the incoming electron. Assuming the electrons satisfy the 2D free electron model, their energy would be given as:

\[ E = \frac{\hbar^2}{2m} (k_{\perp}^2 + k_{\parallel}^2) = E_{\perp} + E_{\parallel} \]  

(2.10)

Where \( m \) is the rest mass of the electron (free electron mass) and \( k_{\perp} \) and \( k_{\parallel} \) are the momentum of the electron perpendicular and parallel to the M/S interface, respectively. The energy of the electron just at the maximum of the Schottky barrier height can now be expressed as:

\[ E = \frac{\hbar^2}{2m^*} (k_{\perp S}^2 + k_{\parallel S}^2) + E_F - eV + \phi_B \]  

(2.11)

Where \( m^* \) is the effective mass of the electron inside the semiconductor, \( E_F \) is the tip Fermi energy, \( \phi_B \) is barrier height at the M/S interface and the subscript of \( k_S \) denotes the momentum in the semiconductor. If we consider the conservation of transverse momentum (which is parallel to the interface \( k_{\parallel} \)) for the electron to enter from metal to the semiconductor, we can obtain an analytical expression for the ‘refraction’ for maximum allowed transverse momentum. Specifically, conservation of transverse momentum defines a critical angle for electron propagation in the metal base outside of which electrons may not be collected in the semiconductor, similar to the acceptance cone at the M/S interface and is defined as [1]:

\[ \sin^2 \theta_c = \frac{m_t eV - \phi_B}{m E_F + eV} \]  

(2.12)

where \( m_t \) is the transverse electron effective mass in the semiconductor \( (m_t = 0.19m \) in Si). This argument would only be convincing for a perfectly epitaxial system without any defects, any deviations of such a system would break the symmetry and therefore conservation of transverse momentum could be relaxed to a certain degree.

2.4.6 BEEM transport models

The tunnel current between tip and top metal based on planar tunneling theory can be written as:

\[ I_T = A \int_0^\infty dE_\perp T(E_\perp) \int_0^\infty dE_\parallel [f(E) - f(E + eV_T)] \]  

(2.13)
$T(E_\perp)$ is the tunnel probability for an electron to tunnel through the vacuum barrier over the transverse and parallel (to the interface) energies, $E_\perp$ and $E_\parallel$. $A$ is the constant related to effective tunneling area, $f(E)$ is the Fermi distribution function, and $V_T$ is the applied tip voltage.

According to widely used Bell-Kaiser (BK) model[1], BEEM transmission is the fraction of the ballistically transmitted tunnel current:

$$I_B = AR \int_{E_{\perp}^{\text{min}}}^{E_{\perp}^{\text{max}}} dE_\perp T(E_\perp) \int_0^{E_{\parallel}^{\text{max}}} dE_\parallel [f(E) - f(E + eV_T)]$$  \hspace{1cm} (2.14)$$

Where $R$ is an attenuation factor due to scattering in the metal base and the M/S interface. According to BK model, $R$ is considered to be energy independent but it can also be weakly dependent on energy. Other parameters, $E_{\perp}^{\text{min}} = E_F - e(V_T - \phi_B)$ and $E_{\parallel}^{\text{max}} = [m_t/(m-m_t)] \times [E_\perp - E_F + e(V_T - \phi_B)]$.

For $V_T$ just above $\phi_B$, close to threshold, above equations (2.13), (2.14) predict:

$$I_B \propto I_T (V_T - \phi_B)^2$$  \hspace{1cm} (2.15)$$

Such quadratic onset considers classical transmission across the M/S interface with parabolic conduction band minimum in the semiconductor. Considering quantum mechanical transmission across the M/S interface another model was given by Ludeke-Prietsch (LP model) according to which $I_B \propto I_T (V_T - \phi_B)^{2.5}$ [3]. It was found that near the threshold regime, no significant difference between the BK and LP models can be resolved beyond experimental error. Increasing the bias voltage approximately 0.2 - 0.3 V above the threshold the BEEM current starts varying linearly with the tip bias showing that the theory only models the BEEM current very close to threshold. For the Schottky barrier extraction in our experimental measurement we have considered BK model instead of LP model and we have seen a better match with the macroscopic $I - V$ measurements.

### 2.5 Techniques related to BEEM

In a standard BEEM experiment, an n-type semiconductor substrate is used as the collector and a negative tip bias is applied to inject electrons into the base. A fraction of the injected hot electrons can then be collected as collector current. Using a positive tip bias, holes can be injected into the base and in order to collect these holes directly one needs to use a p-type semiconductor. So the devices can be fabricated by using either an n-type or a p-type semiconductor. However the use of a p-type semiconductor is not the only way to record BEEM current with a positive
2.5. Techniques related to BEEM

2.5.1 Ballistic Hole Emission Microscopy (BHEM)

The technique of hot electron study in BEEM can equally be well applied for non-equilibrium holes, in a device structure consisting with a p-type collector. The technique is then often referred as ballistic hole emission microscopy (BHEM). The working principle of the technique is as follows: The STM tip is positively biased which injects electrons into the tip, and therefore holes into the base through vacuum tunnel barrier. A fraction of the injected holes that satisfy the energy and momentum criteria are then collected in the valence band of the semiconductor. Ballistic electrons in BEEM are used to probe conduction band structure whereas ballistic holes in BHEM are used as a probe of the valence band structure of the same semiconductor. BHEM was demonstrated by Bell and serves as a direct measurement of the p-type Schottky barrier height. The behavior of a typical BHEM spectrum close to threshold is similar to the BEEM spectrum. The collected current has a $I_{C(Hole)} \propto I_T(V - \phi_B)^2$ dependence, where $\phi_B$ is the Schottky barrier height with a p-type semiconductor. Although BEEM and BHEM are very similar but the distribution of hot holes is exactly opposite to the distribution of hot electrons. The
tunneling electron distribution is peaked at the Fermi level of the negative electrode which is the STM tip in the case of hot electrons and metal base in the case of hot holes and such asymmetry in the distribution causes a difference in hot hole and hot electron scattering at higher biases.

### 2.5.2 Scattering (Reverse) BEEM

The direct electron and direct hole spectroscopies can be used to probe conduction and valence band structure of the M/S interface with n and p-types semiconductor respectively. These mode of operation are considered to be the forward bias experiment where majority carriers are injected and a fraction of them are collected. However, there is another way to study the scattered carriers by probing only those carriers which are created in the process of scattering and is referred to scattering (Reverse) bias BEEM experiment. In the case of n-type semiconductor collector, electrons will be extracted from the metal film creating a ballistic hole distribution in which the technique relies on the detection of only secondary electrons created in the process of carrier-carrier scattering. Such process is very similar to the “Auger like” scattering process.

In the case of R-BEEM process[8], hot holes are injected (electrons are extracted) by the tip to the base and they are filled by electron-hole collisions. Energy of the injected holes transferred to the excited electrons can be maximum up to the kinetic energy of $E_{F,b} + eV_T$. If the secondary electrons have enough energy and momentum to surmount the barrier, they can be collected as collector current with the same sign as direct BEEM. Considering free electrons and zero temperature, R-BEEM transmission can be written as:

$$I_{RB} = AR \int_{E_{F,b} - eV_T}^{E_{F,b}} dE \int_{0}^{E} dE_\perp P(E, E_\perp)T(E_\perp)$$ (2.16)

where $E_{F,b}$ is the base Fermi energy, $P(E, E_\perp)$ is the probability of creation of excited electrons from the injected hot holes. The excited electrons are then collected above $\phi_B$ with proper momentum. Near threshold, the above expression of R-BEEM transmission can be simplified as:

$$I_{RB} \propto I_T(V_T - \phi_B)^4.$$ (2.17)

Considering the quantum mechanical transmission of electrons at the M/S interface, the power of the above equation will be 4.5 (LP model) instead of 4 (BK model) and similarly an analogous R-BHEM experiment can also be performed using a p-type semiconductor.
Direct and reverse BEEM involve electron and hole injection from the tip to the base respectively. It is also important to consider the distribution of injected carriers for scattering in the base. When electrons are injected into the base, the distribution of electrons are maximum at the applied bias to tunnel through. But hole injection is completely opposite. The hot hole distribution is maximum close to the Fermi level of the base so less number of hot holes tunnel through the barrier. Such difference in distribution plays important role for hot electron and hot hole scattering which reflects also in the BEEM and R-BEEM spectral shape.

In case of R-BEEM, collected transmission is also expected to be decreasing with increasing thickness but differently than direct BEEM. Similar exponential decay can be obtained as:

\[
\frac{I_{RB}(t, E)}{I_T} \propto \exp \left[ -\frac{t}{\lambda_{eff}(E)} \right]
\]

(2.18)

\(\lambda_{eff}(E)\) is the effective attenuation length governs by the diffusion length for inelastic collisions. Such characteristic length is the cumulative effect of hole attenuation, creation efficiency of excited electron and then the decay of isotropically distributed excited electron.

2.6 Ballistic Electron and Hole Magnetic Microscopy (BEMM and BHMM)

Ballistic electron magnetic microscopy (BEMM) was first introduced as the magnetic counterpart of BEEM by Rippard and Buhrman in 1999 [9]. The technique is based on the spin-dependent hot electrons scattering in ferromagnetic thin films, in which the minority spin electrons are attenuated more strongly than the majority spin electrons. This is very similar to that of the classical “polarizer-analyzer” experiments of optics where the angle between polarizer and analyzer controls the output intensity of the transmitted beam. Similarly, the BEMM current above the Schottky barrier is high when the magnetizations of both ferromagnetic layers of the spin-valve are aligned parallel (P) and low when they are aligned anti-parallel (AP) controlled by an external applied magnetic field.

The concept of BEMM experiment is very similar to that of the magnetic tunnel transistor (MTT) where the injection of hot electrons is by the STM tip through an ideal vacuum tunnel barrier as shown in Fig. 2.9 instead of a physical barrier. There are two magnetic layers (FM I and FM II) present which are necessary to fabricate the magnetic sensor. The lower normal metal is used for good growth on the n-type semiconductor with a well-defined and homogeneous Schottky barrier at the M/S interface. The middle normal metal is used as a spacer layer. This means that
Figure 2.9: Schematic of ballistic electron magnetic microscopy. The tip of a scanning tunneling microscope (STM) is used to inject hot electrons into a ferromagnetic thin film stack consisting of two ferromagnetic thin films (FM I, FM II), separated by a thin non-magnetic layer (NM). The current in the semiconductor collector depends on the relative orientation of the magnetization of the two magnetic layers. It separates the two magnetic layers, so that they will not interact directly. For an ex-situ transfer of the device from the deposition system to the measurement set up, a capping layer is grown, to prevent oxidation of the top magnetic layer. The injected unpolarized hot electrons by the STM tip become strongly spin polarized as they pass through the ferromagnetic thin films due to spin dependent scattering in the ferromagnetic layers. The collector current strongly depends on the local magnetizations of both ferromagnetic layers. The spin dependent collector current, $I_B$, for the P and AP configuration, can be written as [26],

$$I_B^P \propto (T_{FM1}^M T_S T_{FM2}^M + T_{FM1}^m T_S T_{FM2}^m) \quad (2.19)$$

$$I_B^{AP} \propto (T_{FM1}^M T_S T_{FM2}^m + T_{FM1}^m T_S T_{FM2}^M) \quad (2.20)$$

where $T^M$ and $T^m$ refer to the transmission of the majority (M) and minority (m) hot electrons in the ferromagnetic layers, and $T_S$ is the transmission in the spacer (non-magnetic; NM) layer. When the magnetizations of the two ferromagnetic layers are parallel (P), then only one of the spin-channels (spin minority) will be strongly scattered and the other channel (spin majority) will be less scattered during transport
through the spin valve structure. But when the ferromagnetic layers are in anti-parallel alignment, both of the spin-channels will be strongly scattered when passing through the spin valve structure. As a result the collected BEMM current will be maximum for P-orientation and minimum for AP-orientation. Similar experiment can also be done with the hot holes in a spin valve on a p-type semiconductor and the technique is then called as Ballistic hole magnetic microscopy (BHMM).

**Magnetocurrent (MC)**

As discussed previously, the signal in the P condition will be higher than in the AP condition and a measure of this difference is called as the magnetocurrent (MC). The MC is defined as:

\[
MC = \frac{(I_P - I_{AP})}{I_{AP}} \times 100\%
\]  

(2.21)

Thus the MC is very sensitive to the \( I_{AP} \) and relatively less sensitive to the \( I_P \). The MC can never be below -100%, but it has no upper limit. In an epitaxial spin valve, the MC increases with a high quality interface and a good decoupling between the ferromagnets. Thus in general a higher MC corresponds to the highly efficient spin transport in the spin valve.

### 2.6.1 Resolution of magnetic imaging

By scanning the STM tip over such a spin valve device, a magnetic image of the transmitted electrons can be obtained simultaneously with the surface topography. The contrast of the image gives information about the relative magnetization orientation of ferromagnetic films. An example of such magnetic images is shown in the Figure 2.10. The measurements have been performed by BHMM on a spin valve structures deposited on a p-type semiconductor [25] and Figs. 2.10a and 2.10b show the magnetic images taken on a Co/Au /NiFe spin valve [10] in AP and P conditions respectively. The lighter (darker) areas in the image correspond to the ferromagnetic films being in P (AP) magnetic orientation. For an applied magnetic field of -30 Oe, most of the regions are in AP state with minimum hole current of about 0.55 pA. However, there is a region with narrow ring-like structure with larger hole current which is attributed to the 360° domain wall. For -100 Oe applied field both magnetic layers are saturated and the signal is almost homogeneously bright with larger parallel current. Taking a line cross section across a 360° domain wall, the magnetic resolution can be determined as shown in the Fig. 2.10c. The line profile is described by a simple arctan function (solid line) for one side of the wall and the upper limit of the magnetic resolution is determined to be 28 nm. In this thesis in
Figure 2.10: BHMM images taken on a Co/Au/NiFe spin valve in subsequent magnetic fields of (a) - 30 Oe (AP) and (b) -100 Oe (P) at $V_T = -1.6$ V, $I_T = 3$ nA, $T= 150$ K of scanning area $2 \times 2 \mu m^2$. Hole current ranges from 0.5 pA (black) to 1.1 pA (yellow). In (c), a cross section is shown taken along the white line marked in (b). Taken from Ref [10].

chapter 6, we have demonstrated magnetic resolution using hot electron current in BEMM experiment which is below 20 nm.

2.7 Summary

In summary, the concept of hot electron and its ballistic transport in a metal based solid state device (macroscopic) with few important examples from the literature are discussed. Then, the basic working principle of the microscopic or local technique i.e. ballistic electron emission microscopy and how it has been extended for the imaging of magnetic domains in a spin valve device structure are described. Different modes of the technique which can be used for direct hot electron, direct hot hole and scattered hot carriers transport through the over-layer and locally probe the metal-semiconductor interface are also highlighted. An introduction to BEEM theory has been described using Bell-Kaiser model which has been used for the local Schottky barrier extraction. The experimental demonstration of the resolution of BEEM and BHMM have been presented with few earlier examples from the literature and issues regarding resolutions are also discussed.
Bibliography
