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The influence of internal and external electric fields on the transport of energetic electrons in nanostructures

Mario Marpe[a], Andreas Wucher[a], Detlef Diesing[b,*]

[a] Faculty of Physics, University of Duisburg-Essen, 47048 Duisburg, Germany
[b] Institute of Physical Chemistry, Faculty of Chemistry, University of Duisburg Essen, 45117 Essen, Germany

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ABSTRACT

Sandwich like metal–insulator–metal (MIM) nanostructures consisting of a 50 nm silver film and a 30 nm aluminum film separated by a few nanometer aluminum oxide layer were irradiated with a focused e-beam (diameter 0.5 mm) at kinetic impact energies in the range of 100 eV to 1000 eV. To distinguish between *internal* transport of hot charge carriers across the buried insulator (tunnel junction) and parasitic electron transport mediated by *externally* emitted electrons re-entering the sample, an additional "dome" electrode was implemented which was biased to positive or negative potential in order to establish an external accelerating or retarding field above the nanostructure's surface. Different device currents induced by the primary electron irradiation were measured either by metering the irradiated or non-irradiated electrode, respectively. The dependence of the detected device currents on impact parameters such as the irradiated position on the MIM surface, the kinetic energy and impact angle of the primary electrons was studied. These experiments were accomplished while changing the internal electric field by an *internal* bias voltage between the top and the bottom electrode of the MIM and while changing the external electric field by applying a voltage to the dome electrode. The measured currents are interpreted in terms of *external* and *internal* emission yields. It is shown that the external electric field allows a clear discrimination between true *internal* electron transport and *external* electron transport leaving the MIM nanostructure on one site and re-entering at another site. The results demonstrate that "internal" currents measured without an external dome electrode may be strongly influenced or even falsified by such cross-absorption effects.

1. Introduction

Kinetic electron beam induced electron emission from solid samples is the basis for the image forming process in **s**canning **e**lectron **m**icroscope (SEM) [1]. The electrons being re-emitted from the sample are conventionally classified in so-called (i) secondary electrons with an energy lower than 50 eV and (ii) back scattered electrons with energies above 50 eV up to the energy of the primary electron beam E_{prim} [2]. The secondary electrons can also be used for the image formation process in a SEM by acceleration mediated by a grid electrode and subsequent detection in a scintillation process [3].

Kinetic ion beams are known to produce also so-called internal electronic excitations inside an irradiated solid [4–7]. These internal excitations are evoked by the deceleration of projectiles inside the solid. The energy transfer to the target's electron gas during this stopping process is surprisingly high even for low kinetic energies $E < 10$ keV [8].

These normally hidden internal electronic excitation processes in the bulk of a silver film was studied by thin film metal–insulator–metal (MIM) nanostructures via monitoring the internal electron emission over the only several nm thin insulator barrier [9]. This internal emission process was later on used to characterize a multitude of electronic excitations induced for example by (i) chemical surface reactions [10] (ii) photo excitation [11,12] (iii) two photon photo illumination [13] or (iv) Auger disexcitation of highly ionized ions [14,15]. MIM devices offer also the unique possibility to detect excited electrons as well as excited holes. The selection of the detection mode is realized by the application of a bias voltage between the two metals [16]. Despite the variety of experiments, a careful study comparing the internal electron emission over the insulator barrier with the external electron emission over the metal's surface barrier was missing.

Recently, a first comparison of internal and external electron emission was made by irradiating MIM devices with a focused electron beam at impact energies between 100 eV and 1000 eV [17]. It could be

* Corresponding author.
E-mail address: detlef.diesing@uni-due.de (D. Diesing).

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proven that the impact of the primary electron beam leads to a measurable device current between the two metal electrodes in addition to that current generated by *external* electron emission into the vacuum, but the partitioning between *internal* and *external* emission processes could not be uniquely deduced from the experimental data. In particular, the question remained unanswered whether the measured "*internal*" current was entirely due to hot charge carriers traversing the tunneling junction, or whether it was somehow influenced by *externally* emitted electrons circumventing the *internal* tunnel barrier.

In order to clarify this point and investigate possible issues arising from secondary electron emission when nano electronic devices are studied in a SEM [18], an external electric field was applied to an electron irradiated MIM nanostructure. The MIM nanostructures were produced in a cross configuration with a 30 nm-thick aluminum "bottom" and a 50 nm-thick silver "top" electrode separated by a 3 nm-thick aluminum oxide layer produced by anodic oxidation. The anodic oxidation is a consumptive process leading to an aluminum thickness slightly thinner than 30 nm [19].

In the previous study mentioned above, external and internal emission currents were measured as a function of electron energy and impact point of the electron beam on the MIM structure [17]. In addition, an internal electric field was generated across the oxide film by applying a bias voltage of up to ± 1 V between the top silver and the aluminum bottom electrode. It was found that the e-beam induced internal device current was surprisingly large and moreover practically independent of the primary electron energy and impact angle. From these results, it was suspected that external electron emission may have to be included in the interpretation of apparently internal transport currents measured in such a device, and the addition of an external electric field was suggested in order to address this question. The experiments presented here therefore represent a continuation of that work. An additional electrode above the irradiated sample surface was added in order to generate such an external field and investigate its influence on the measured device currents. The polarity of the field is either chosen such as to accelerate secondary electrons away from the irradiated surface, as in the conventional Everhart-Thornley [3] setup, or the field is used with opposite polarity to repel the secondary electrons back to the sample. By this method it is possible to manipulate and control the external emission process allowing to study its influence on the measured internal device current.

2. Experiment

2.1. Setup

100 eV to 1000 eV electrons impinging on the several 10 nm thick electrodes of a metal–insulator–metal sandwich system will in part be elastically reflected (in the following referred to as "**back-scattered electrons**" or BSE) and partly cause an emission of low-energy secondary electrons (in the following referred to as "**secondary electrons**" or SE). Both processes generate a current of electrons which are emitted back from the irradiated surface area into the vacuum. In this work, an additional halfpipe-like "**dome electrode**" set to a variable potential produces a defined external electric field above the irradiated sample.

Depending on the voltage U_d applied between the dome electrode and the irradiated surface, this external electrode can either act as collector or as a repeller for beam induced electrons leaving the sample.Experiments have shown that values of $U_d = \approx \pm 40$ V are sufficient to completely repel or collect the externally emitted low energy secondary electrons, respectively (as shown later in Fig. 11). A slit of ≈ 4 mm width in the dome electrode allows the focused primary electron beam (diameter of ≈0.5 mm) to travel unobstructed to the sample. The current of electrons back reflected to the dome electrode can be measured, thereby permitting experiments similar to the usual electron spectroscopy setup with an external collector. The currents into the different electrodes of the irradiated MIM device are measured

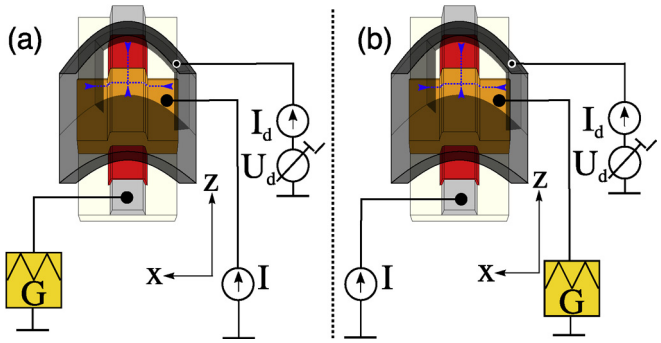

Fig. 1. Schematic of the set-up: (a) *probe top* mode where the current into the silver top electrode (orange) is measured while keeping the aluminum bottom electrode (light gray) at a constant potential. Silver and aluminum are separated by a 4 nm thick oxide layer (red). The dome electrode (dark gray) is kept at U_d while metering the current I_d to the dome. The sample is either moved horizontally in *x*-direction or vertically in *z*-direction as symbolized by the blue dashed lines while detecting all currents as a function of the momentary beam position. (b) **probe bottom** mode where the current into the aluminum bottom electrode is measured and the silver top electrode is kept at a constant potential. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

using the current-monitoring input of a potentiostat (Heka PG 510). If the current into the top silver or bottom aluminum electrode of the MIM is measured, the experiment mode is called "**probe top**" or "**probe bottom**", respectively. In both modes, the electrode which is not metered is connected to the "counter electrode" terminal (marked with the character G for generator in 1) of the potentiostat and kept at a constant potential, usually at 0 V with respect to the other MIM electrode unless a bias voltage is applied.

Depending on the position of the impact point on the MIM device and the measurement mode (*probe top* or *probe bottom*), two different experimental scenarios are possible (see also the table in Fig. 2):

- In case that the current into the electrode that is irradiated by the primary electron beam is read out, this is called a **direct experiment** and the measured currents are assigned as I_{dir}.
- In case that the current in the non-irradiated electrode is read out by the current meter, this is called an **indirect experiment** and the measured currents are assigned as I_{indir}.

Since U_d was limited to ± 40 V in this work, predominantly low energy SE emitted from the irradiated surface with a maximum kinetic energy of about 50 eV [20] are influenced by this voltage. Backscattered electrons, which mostly undergo only one quasi-elastic interaction in close vicinity to the surface causing only a relatively small energy loss, will be influenced to a much smaller extent. For the highest kinetic impact energies used in this experiment ($E_{kin} \leq 1000$ eV), the influence of the dome voltage on the flux of backscattered electrons can therefore safely be neglected. For both polarities of U_d, these backscattered electrons may therefore hit the dome electrode and can thereby produce a flux of tertiary electrons, which is again composed of BSE and SE. In the case of a negative dome voltage, the low energy SE are accelerated towards the sample and held back otherwise. As a consequence, the measured currents I_{dir} and I_{indir} will be influenced by the polarity of the dome voltage. In case of $U_d > 0$ V, the superscript "+" is used and "−" otherwise, leading to four different measured current values I^+_{dir}, I^-_{dir}, I^+_{indir} and I^-_{indir}, respectively.

All currents were measured as a function of the geometrical impact point of the primary electron beam on the MIM device as sketched in Fig. 2. The location of the impact point is characterized by *(x,z)* coordinates, where the *x*-direction is aligned parallel to the top silver electrode strip and the curved shape of the dome electrode (see Fig. 1). The dome electrode is therefore sketched as a section of an ellipsoid in