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High-energy electron emission from MIS-structures

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The effects of electric field induced electron emission from complex emitters are studied. As the emitters were used thin ITO (indium tin oxide) films deposited on a glass plate. The ITO film was subjected to the bombardment by a primary electron beam or illuminated by the UV light. The field induced secondary electron emission (FISEE) was studied in the 10^{-7} hPa vacuum. En ergy examination of the emitted electrons revealed some electrons of energy higher than E_p. The electron emission still existed due to the applied field and UV illumination after stopping the bombardment by the primary beam (field induced electron emission and photoemission – FIEE and FIPE). About 80% of the emitted electrons were found to have energy within 1–2 eV (few percent – 10 eV). The phenomenological model of the field induced emission effects was proposed. The main assumptions of the model are supported on the basis of the field induced division of the ITO film into two zones: with depleted and enhanced number of electrons.

1. Introduction

Thin, flat dielectric films can be low macroscopic field electron emitters, able to generate electrons when subjected to a macroscopic electric field in the range of $10^6 - 10^7$ V/m. Deposited on a conducting substrate and operated in vacuum, the film emits electrons when a strong electric field is applied. Carbon-based films can be electron emitters, and their potential as broad-area sources has been widely discussed [1]–[3]. Earlier examples of the field induced emission from thin dielectric films and of low macroscopic field emission [4], [5] have also involved phenomena difficult to explain [6]–[9]. Electron emission from oxide dielectric films was systematically investigated by MALTER [6]. Malter electron emission is from thin films of high-resistivity materials with high-secondary-electron coef-ficients, induced by a primary electron beam directed at the film front surface. This beam induces positive space charge distributions in the oxide, and the emission can persist when the primary beam is turned off, in some cases indefinitely. The explanation of the Malter emission is that a strong positive charge layer is created at or near the film front surface that either discharges very slowly or is self-sustaining. The positive charge layer creates a strong internal electric field

that acts on the substrate/film interface. Band bending in the film is assumed to create a depletion region and the positive space charge close to the back interface.

2. Measurement set and samples

In order to fabricate the samples the cover glass plates of the type "Micro" were used, on which the oxide conductive layers of SnO_2 and In_2O_3 (ITO) were deposited using the constant current reactive ion scattering technique [10]–[12]. In this work, the layers of thickness from 10 to 250 nm were subjected to examination. In the case of the studied ITO layers, their resistivities fall in the range from 8×10^{-4} Ωcm to 3×10^{-3} Ωcm. The resistance was measured using the four electrode method [13]. The energy gap was found to be 3.5 to 4 eV wide. The samples were of rectangular shape of dimensions $0.2 \times 16 \times 16$ mm with ITO layers deposited on the both sides. One of the layers of thickness between 10 and 250 nm was the electron emitting surface, while to the other one, 1 μm thick, the polarizing voltage U_{pol} was applied (the field electrode). Thick SnO_2 and In_2O_3 layers (doped by Sb and Sn) belong to degenerated semiconductors of properties similar to metals. This is the reason why the ITO layer of thickness 1 μm was a well-conducting field electrode.

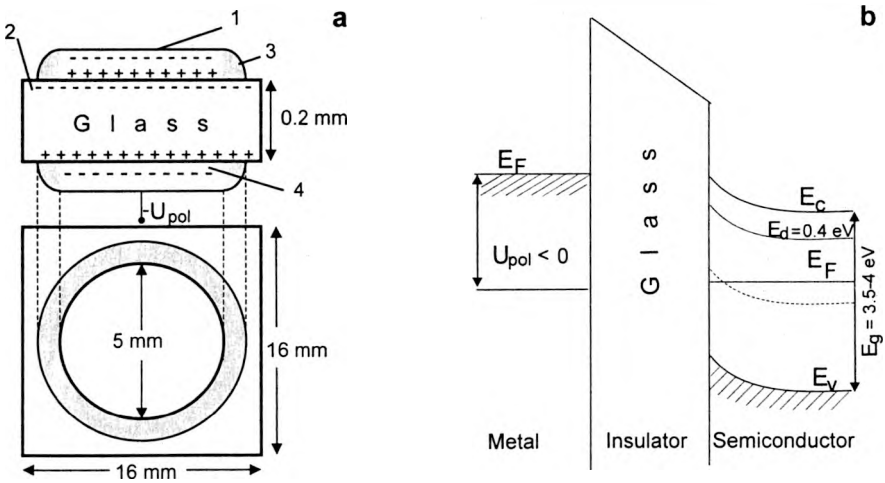

Fig. 1. Shape and size of a sample: 1 – layer of ITO, 2 – glass substrate, 3 – conducting paste, 4 – field electrode (**a**). Energy diagram of the field electrode–insulator–ITO (MIS) system; E_g – energy gap, E_d – donor level (**b**).

Figure 1 presents the shape and size of a sample (**a**) and the energy diagram of the field electrode–insulator–ITO (metal–insulator–semiconductor, MIS) system (**b**).

A scheme of the electric set used to study the secondary emission effect is presented in Fig. 2. The four-grid analyzer with the electric retarding field enables the study of the secondary electron energy distribution. To obtain the secondary

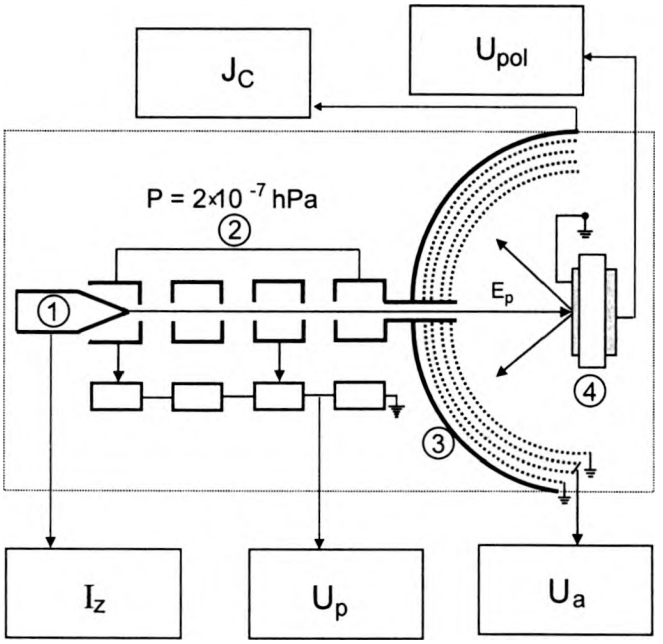

Fig. 2. Experimental set-up for investigation of the FISEE. 1 – electron gun CL-305, 2 – accelerating system, 3 – four-grid retarding potential analyzer, 4 – sample, I_z – cathode heating current, U_p – accelerating voltage, U_a – analyzing voltage, U_{pol} – polarizing voltage, J_c – collector voltage.

electron energy distribution, the negative potential U_a relative to the emitting surface of the sample is applied to the analyzing grids. The measurements were carried out in 2×10^{-7} hPa vacuum [14].

The electron emission still existed due to the applied electric field and UV illumination after stopping the bombardment by the primary beam. It should be pointed out that the total current of the electron flux is relatively small. This implied the use of the electron multiplier and the multichannel amplitude analyzer [15], [16]. The application of the polarizing voltage U_{pol}, within the range from -2 kV to 0 V, to the field electrode creates an internal field that favoures electron emission into vacuum. Appropriate operational conditions for the electron multiplier were received by acceleration of electrons between the emitting film and the multiplier, *i.e.*, voltage $U_p = -200$ V at the emitting film and grounded input of the multiplier. The electrons accelerated to the energy eU_p create the voltage pulses in the multiplier. The pulses are recorded in the channels of the pulse analyzer, creating the so-called voltage pulse amplitude spectrum. The amplitude spectra were measured for dark samples and samples illuminated by a quartz lamp.

3. Results

The energy spectra in the FISEE from glass – ITO structures were obtained using the retarding field. The exemplary curves representing the spectra $F(E) = f(E)$ are

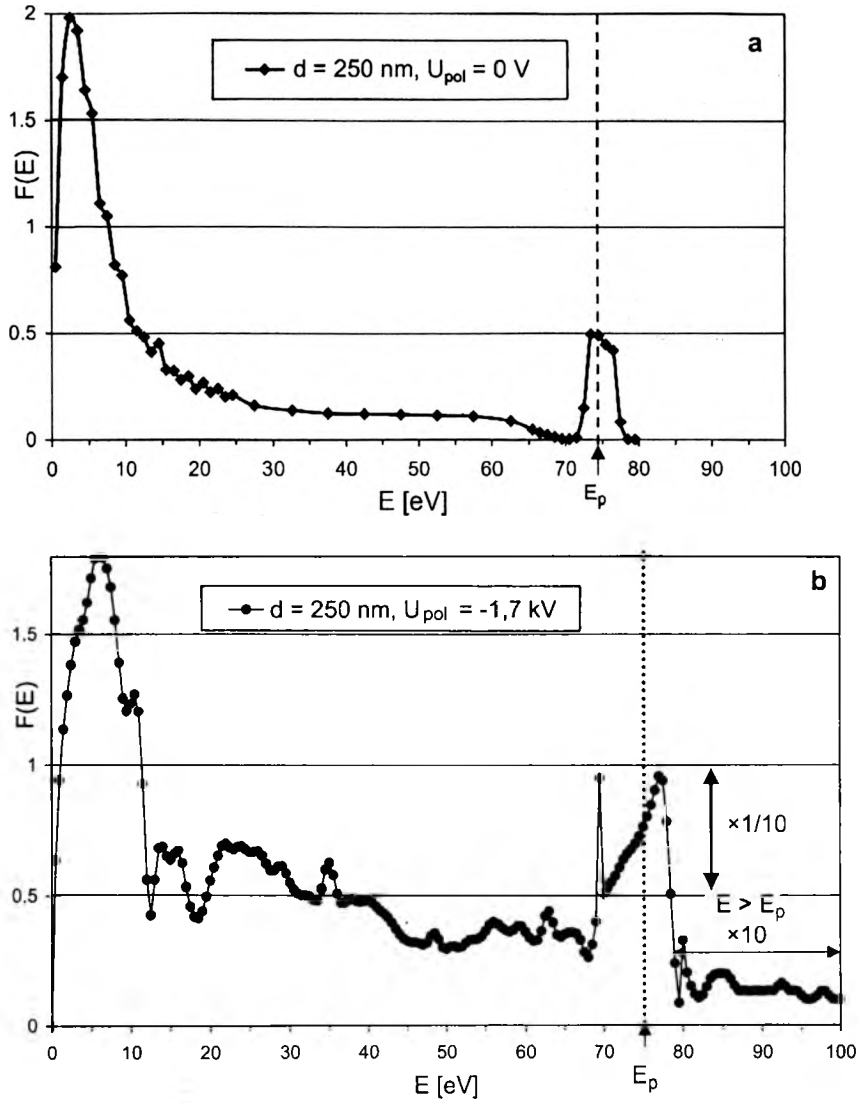

Fig. 3. Energy distributions of secondary electrons for $E_p = 75$ eV (FISEE); **a** – $d = 250$ nm, $U_{pol} = 0$ V, **b** – $d = 250$ nm, $U_{pol} = -1.7$ kV.

shown in Figs. 3 and 4. Figure 3a shows a typical energy distribution of secondary electrons when $U_{pol} = 0$ V. It points to the fact that the majority of electrons are subjected to a considerable energy loss while a much smaller number of them collide elastically. Paper [14] shows that in the dependence $\delta = f(U_{pol})$ there are the minima as well as the maxima. The energy spectra, where the negative voltage U_{pol} was a parameter, were found to change with the voltage U_{pol}. In Figs. 3a and 4 are indicated the values of the voltage U_{pol} and the ITO layer thickness for which the high-energy electrons of energies higher than that of the

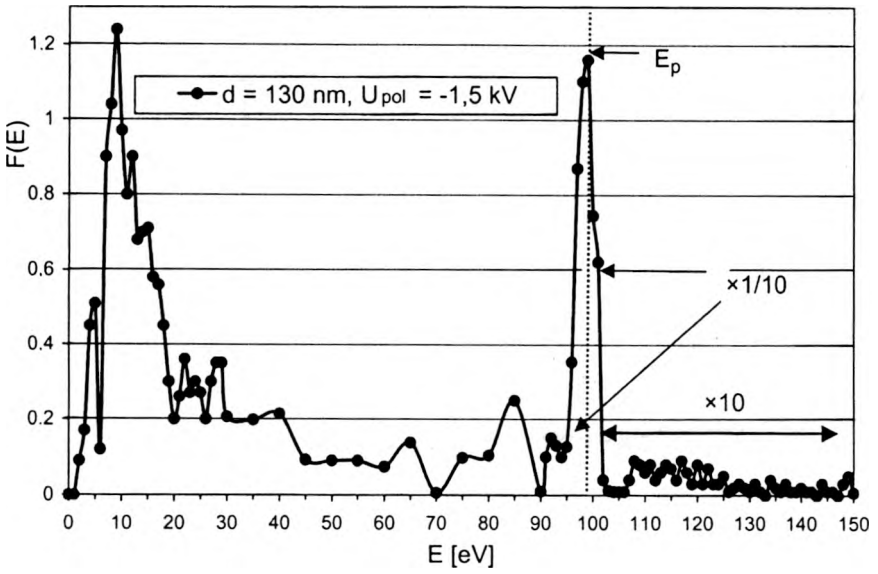

Fig. 4. Energy distributions of secondary electrons for $E_p = 100$ eV (FISEE); $d = 130$ nm, $U_{pol} = -1.5$ kV.

primary electrons were obtained. The number of such electrons was found to be relatively small, that is why the $F(E)$ values were multiplied by 10 in these spectra. It also follows from these curves that the primary peak apparently is higher in comparison with the spectrum shown in Fig. 3 (for $U_{pol} = 0$). It shows that the high-energy (exceeding the primary electron energy E_p) electron number evidently increased. It can be mentioned that the high-energy secondary electrons were found to occur in the experiments carried by IBACH [17], [18]. The author explained this fact by the effect of interaction between the primary electrons and phonons.

The electron emission still existed due to the applied field and UV illumination after stopping the bombardment by the primary beam. The electron energy in the cases of the FIEE and FIPE were also determined by the retarding field method. Not the electric current but the values of the voltage pulses (created by electrons) from the electron multiplier output were measured. At first, the amplitude spectra of the pulses were recorded for different retarding voltages U_a and the constant polarizing voltage U_{pol}. Next, for each voltage U_a (that means for each spectrum) the frequency of pulses n (in cps) was determined. Differentiation of so obtained in retarding curves $n = f(U_a)$ gives the energy distributions $F(E) = f(E)$. As it follows from Fig. 5, the majority of electrons emitted in the FIEE and FIPE effects were found to have energies about 2–3 eV; the number of electrons not exceeding 10 eV amounts to 80%. However, it is apparent that the spectrum spreads to about 20 eV. The majority of electrons emitted under the high fields ($U_{pol} = -2$ kV) appear to be the low-energy electrons. This fact could be explained by the existence of the cooling effect of electrons being a result of increased probability of inelastic

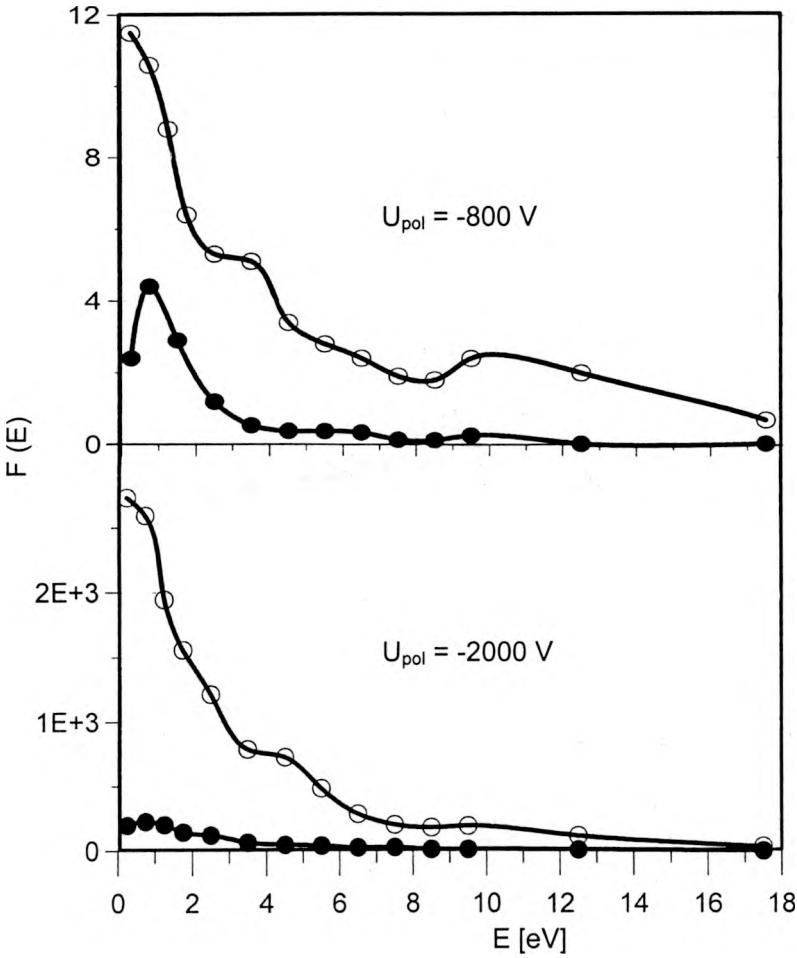

Fig. 5. Energetic spectra for the field and the UV light induced electron emission (FIEE and FIPE). ○ – unilluminated, ● – illuminated, $d = 10$ nm.

collisions of electrons at the high fields (in this condition the production of hot electrons increases). A theoretical model of hot electrons in island metal films deposited onto a dielectric substrate is presented by FEDOROVICH *et al.* [19].

4. Conclusions

The complex structures of the sandwich (MIS) type can be applied as the field- and photo-induced emitters of high-energy electrons. The field intensity inducing these processes should be, at least, of the order of 1 MV/m. In the case of a thick dielectric substrate (0.2 mm glass) the electron collisions and generation of hot electrons take place in the ITO layer or in the glass–ITO interface region, depending on the ITO layer thickness.

The creation of high-energy secondary electrons in the FISEE effect could be explained with the aid of the qualitative model of division of the ITO layer into two zones with the depleted and enhanced number of electrons:

– when a primary electron gets into the enriched zone it may at most cause an increase in the concentration of conduction electrons, with possible appearance of the so-called hot electrons,

– when a primary electron penetrates through the enriched zone, two phenomena may occur simultaneously; electrons in the depleted layer are released into the conduction band or, as a result of retardation in the electric field, a primary electron changes its direction or even produces secondary electrons in cascade multiplication.

Electrons moving in the enhanced zone easily lose their energy, while inside the depleted zone it is quite possible that depending on the free path length of electrons they can achieve a relatively high energy from the field. Electrons of energies higher than E_p are those which do not lose their energies and pass the enhanced layer, for instance by the tunnel effect.

High-energy electrons in the FIEE and PIEE occur due to the heating effect of electrons at the high electric fields. This process leads to the collision ionization, as well as to the avalanche development. As it was shown in paper [20] the electric field of the order MV/cm can create defects, pores and lossless channels dimensions of which are of the range of nanometers. It enables developing the avalanche effects. Illumination of the layer leads to the increase in electron yield. However, it does not effect the electron energy, what is shown in Fig. 5. The electron yield is increasing but the electron energy is not changing what is connected with the appearance of the cooling effect.

The high-energy electron transport mechanism can be interpreted by assuming the creation of defect conglomeration process. The simple oxygen vacancy, as a defect precursor, is transformed by electron load to a twofold coordinated silicon center. These single defects may cluster to complex defects. This cannot exclude the possibility that these defects form injection tips at the interface SiO_2-ITO, as there appears a certain oxygen deficit [20]. These injection tips may grow to the defect channels and may form a free-flight like channel enabling electrons to emit into the vacuum. The energy distribution consists of heated-up primary electrons, of low-energy secondary electrons, as well as of primary electrons strongly cooled down due to impact excitation. Only at certain flight distances and field strengths the beginning of avalanching appears. However, this hypothesis should be proved more accurately.

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