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Certain effects of field and light induced electron emission from indium thin oxide (ITO) layers

JADWIGA OLESIK

Jan Dlugosz University, Institute of Physics, al. Armii Krajowej 13/15,
42-201 Częstochowa, Poland; e-mail: j.olesik@wsp.czest.pl

Indium thin oxide (ITO) layers were deposited onto both surfaces of a glass substrate. One of the layers was a field electrode and negative voltage has been applied to it in order to create the internal electric field. Another one was treated as the electron-emitting layer. The studies were carried out in the 10^{-7} hPa vacuum. As a result of applying polarizing voltage U_{pol} and illuminating by a quartz lamp, photoelectrons are released and enter the electron multiplier. Voltage pulses from the multiplier are recorded in the multichannel amplitude analyzer, creating so-called voltage pulse amplitude spectrum. Dependence of electron emission yield on both the intensity of internal field and illumination was measured. With the increasing the U_{pol} voltage, the count frequency of pulses grows monotonically. At higher U_{pol} (> |–1 kV|) this dependence is exponential. After illuminating the yield of the field induced electron emission grows as well. The cascade multiplication of electrons, which is responsible for the high emission yield, develops under the influence of the electric field of the order of 1 MV/m. The Gauss approximation suggests that the internal electric field in the interface between a glass and ITO layer has to be taken into account.

Keywords: semiconductor, electric field, optical properties, indium tin oxide (ITO), MIS- structure, field effect, electron emission.

1. Introduction

In certain conditions in some semiconductors the non-equilibrium conditions may appear. These effects can occur due to the charge carrier concentration fluctuation at different points of the volume and creation of the momentary variation space charge. The effects are the basis for operation of many electronic devices showing the negative differential resistance such as the tunnel diode or the Gunn diode. As a result, the semiconductor becomes electrically heterogeneous because of creation of accumulation and depletion layers. Many electronic devices operate on the basis of the volume effects occurring due to the external interaction such as applied voltage or illumination. One of the best known devices is a photoresistor, in which due to illumination the bulk resistance may change as a result of the free charge carrier generation in the intrinsic or doped semiconductors. In microelectronics the first observed Gunn effect has found application [1, 2]. This effect is connected with creation of domains where strong electric fields, about 10^3 V/cm, occur.

MALTER [3, 4] was the initiator of the study of the anomaly electron emission effects in dielectrics. The electric field was created in Al_2O_3–Cs_2O, which was charged as a result of its bombardment by an electron beam. However, in Malter's work the electric field was created in an uncontrollable way. We have studied the secondary electron emission phenomenon in the glass–ITO system [5]. Based on Malter's effect, the investigation of the electron emission phenomenon with an inner electric field in the sample was carried out. Applying appropriate U_{pol} voltage to one of the layers an inner electric field of a given direction and value may be created in a controllable way. Additionally, the sample was illuminated by UV light. We call the above effects the field and light induced electron emission.

2. Experimental part

Two conducting films were evaporated on both sides of a microscopic cover glass (16×16 mm) – Fig. 1. One film, In_2O_3:Sn (ITO) of the thickness in the range from 10 to 300 nm was the emitting surface. The other of 1 μm thickness was polarized in order to create an internal field (field electrode). Deposition of ITO films was performed by the dc reactive sputtering technique. The detailed account of the deposition system may be found elsewhere [6–10].

The doped ITO layers appear to be wide gap *n*-type polycrystalline semiconductors, the conductivity of which depends, among others, on doping concentration [11–13]. The band gap was found to be from 3.5 to 4 eV wide. At a doping concentration of about 10^{25} m^{-3}, the donor levels split and the semiconductor becomes degenerated.

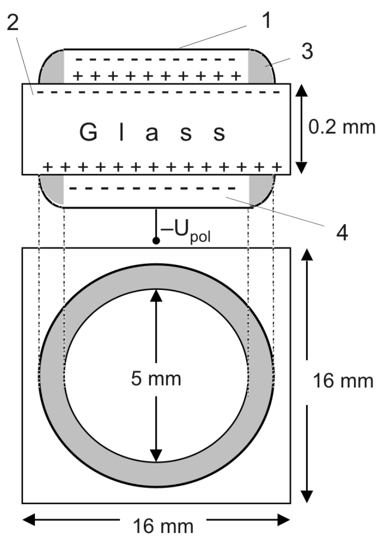

Fig. 1. Shape and size of a sample: 1 – layer of ITO, 2 – glass substrate, 3 – conducting paste, 4 – field electrode.

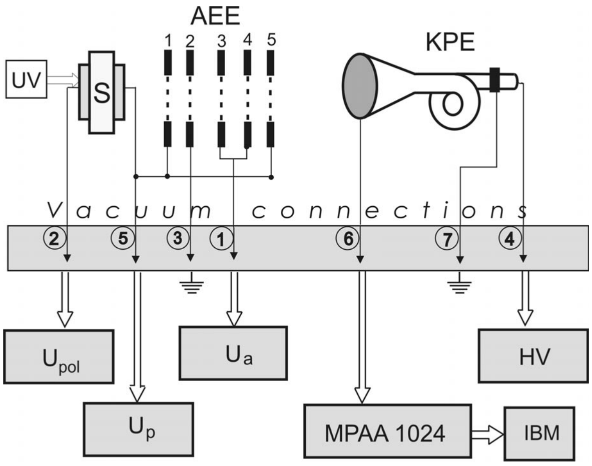

Fig. 2. Experimental setup for investigation of field induced electron and photoelectron emission. S – sample, AEE – electron energy analyzer (1, 2, 3, 4, 5 – grids), KPE – channeltron KPE∅7, UV – XBO150 quartz lamp, vacuum connection: ① – U_a, ② – U_{pol}, ③, ⑦ – earthed, ④ – channeltron supply HV, ⑤ – U_p, ⑥ – multichannel pulse amplitude analyzer (MPAA).

Electric and optical properties of these films are described in [14–17]. The measurements were performed at a pressure of about 2×10^{-7} hPa. The sample as well as an electron energy analyzer and electron multiplier were placed in a vacuum (Fig. 2).

Applying the polarizing voltage U_{pol} (from –2 kV to 0 V) to the field electrode makes an internal field which favours electron emission into vacuum. Appropriate operational conditions for the electron multiplier were obtained by acceleration of electrons between the emitting film and the multiplier, *i.e.*, voltage $U_p = -200$ V applied to the emitting film and grounded entrance of the multiplier.

Depending on the kind of measurements performed, grids 3 and 4 of the energy analyzer were either grounded or polarized by the negative analyzing voltage U_a. The electrons accelerated to the energy eU_p create voltage pulses in the multiplier, which are recorded in the multichannel pulse amplitude analyzer (Tristan 1024) according to their height, creating the so-called voltage pulse amplitude spectrum. The amplitude spectra (for various U_{pol}) were measured for not illuminated samples and illuminated by a XBO 150 quartz lamp.

3. Results and discussion

Figures 3–7 show the amplitude spectra for different voltages applied. A plot of the number of pulses recorded during 500 seconds *vs.* the height of the pulses in mV has been made. The impacts of the illumination of the ITO sample have been studied as well. These dependences have been obtained under the simultaneous influence of the applied voltage and illumination of the sample.

3.1. Amplitude spectra and decomposition into Gaussians

From Figure 3 it can be seen that the experimental curves are approximately bell-shaped, so the attempts have been undertaken in order to adjust the theoretical curve to the experimental one by finding a few curves of the Gauss shape and adding

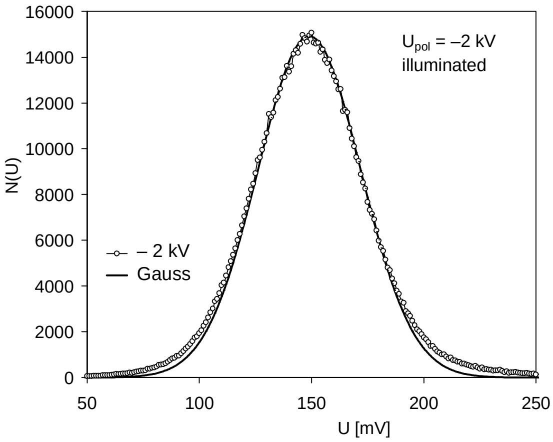

Fig. 3. Pulse amplitude spectrum and approximation by the Gaussian curve at $U_{\rm pol}$ = –2 kV.

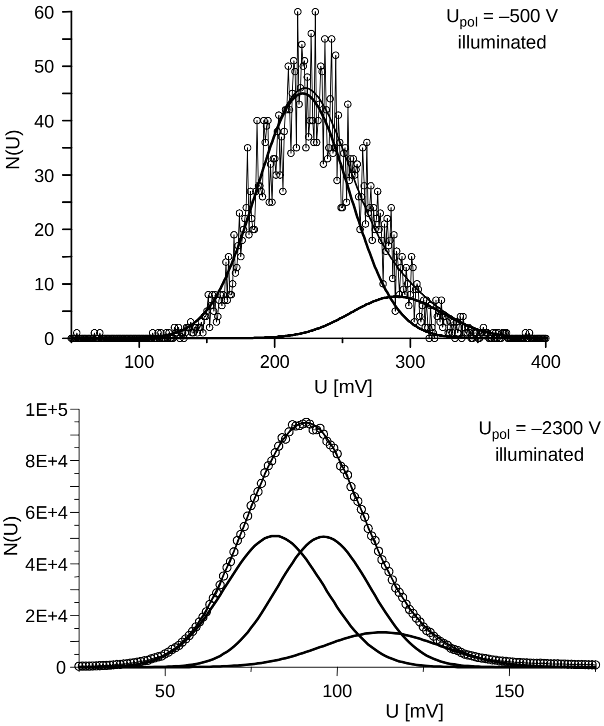

Fig. 4. Pulse amplitude spectra and decomposition into Gaussian curves.

them to create a single curve. Some of the experimental curves can be described satisfactorily by a single Gauss curve, for instance when $U_{pol} < |-1\text{ kV}|$, in dark, the rest of the curves – only partly, for instance when $U_{pol} = -1500$ V. Some of the curves cannot be described by a single Gauss curve, for instance when $U_{pol} = -2$ kV, illuminated. Figure 4 shows that 2 or 3 Gaussians can describe such cases. The computer program was used to decompose the spectrum into the Gaussian components (the sums of the Gauss functions) [18].

From Figs. 3 and 4 one can see that for large U_{pol} under illumination, the experimental curves indicate "tails" for low as well as high amplitudes. In this case, approximation should involve three Gaussians. For lower U_{pol} a difference between experimental and theoretical curves appears mainly for higher amplitudes and two Gaussian approximation is then sufficient.

3.2. Mean amplitude of the spectrum

The results of studies into the field induced electron emission indicate that:

– the mean amplitude of recorded spectrum (amplitude for maximum of spectrum) shifts in the direction of the smaller amplitudes with the rise of the applied voltage U_{pol};

– reduction of the mean amplitude of the spectrum is connected with the increase of the total number of pulses, that is, with the electron emission intensity into a vacuum.

In Figure 5, there are shown two spectra for the same $U_{pol} = 1000$ V, but one has been obtained under UV illumination. It is evident that the photoemission effect causes a considerable increase in the pulse number and also the shift of the mean amplitude by 67 mV compared to the dark spectrum at the same voltage. In Fig. 6, a family of spectra are shown at different U_{pol}, while the sample was illuminated. In order to present the spectra with the small number of pulses a logarithmic scale was chosen. Figure 6 shows a decrease of the mean amplitude with the applied voltage increasing. When the voltage rises from 0.5 to 2 kV, the amplitude decreases by about 50 mV for the illuminated ones. We believe that these effects are connected with the rising number

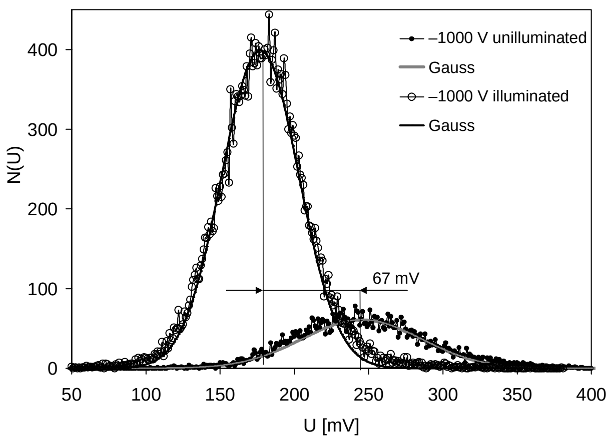

Fig. 5. Pulse amplitude spectra for $U_{pol} = -1000$ V. The illustration of the mean amplitude shift.

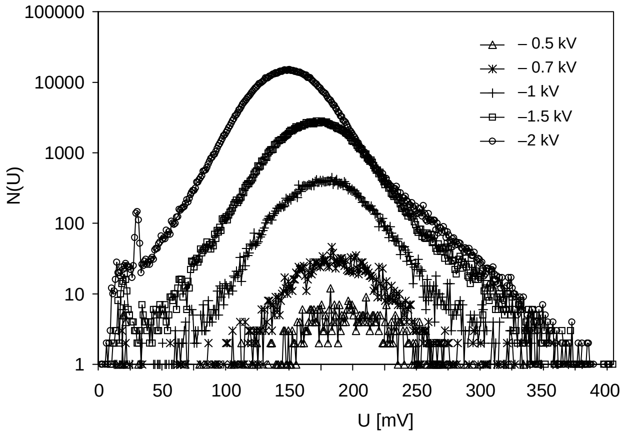

Fig. 6. Some pulse amplitude spectra for U_{pol} as a parameter after illumination of the sample.

of emitted electrons independently of the cause of increment. This is because shifts of the maximum are smaller for the photoemission case.

3.3. Hysteresis effect

The shift effect has also been found during the repeated measurement of the spectra at the same voltage applied. The measurement course in one case was performed when the applied voltage changed from 0 V to –2 kV and in the second case in the reverse direction, from –2 kV to 0 V. Both spectra have been found to be different. They differed by the total number of pulses as well as by the mean amplitude connected with the mean energy of the emitted electrons. Figure 7 shows the results of these studies.

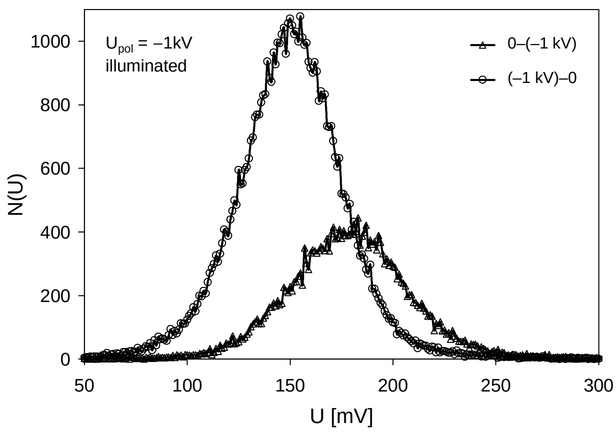

Fig. 7. Hysteresis effect for U_{pol} = –1000 V. 0–($-U_{pol}$) – variation of U_{pol} in the direction from zero to $-U_{pol}$; ($-U_{pol}$)–0 – variation of U_{pol} in the direction from $-U_{pol}$ to zero.

The change in direction of the applied voltage is indicated in the figures by 0–(–U_{pol}) and (–U_{pol})–0. When U_{pol} changes in the reduction direction, the total pulse number was always found to be larger than in the rise direction. We believe that this effect is connected with generation of the free electrons by the strong field and after some avalanche effects they are emitted with a delay into vacuum. It is possible that electrons are likely to be entering the surface layer of ITO where their concentration is high (accumulation effect by the applied voltage). Electrons, in order to escape into vacuum, suffer the loss in energy due to the larger amount of collisions with other electrons and the atoms. Due to this, the emitted electrons show reduced mean energy. So, we have shown the hysteresis effect in the field induced electron emission phenomena.

3.4. Electric field induced secondary emission

In the previous studies of electric field induced secondary electron emission from ITO layers, some anomalies have been noticed as well [5]. One of them was the field modification of energy distribution in the secondary electrons. The modification concerned certain voltages applied at which there was observed a shift of the elastic

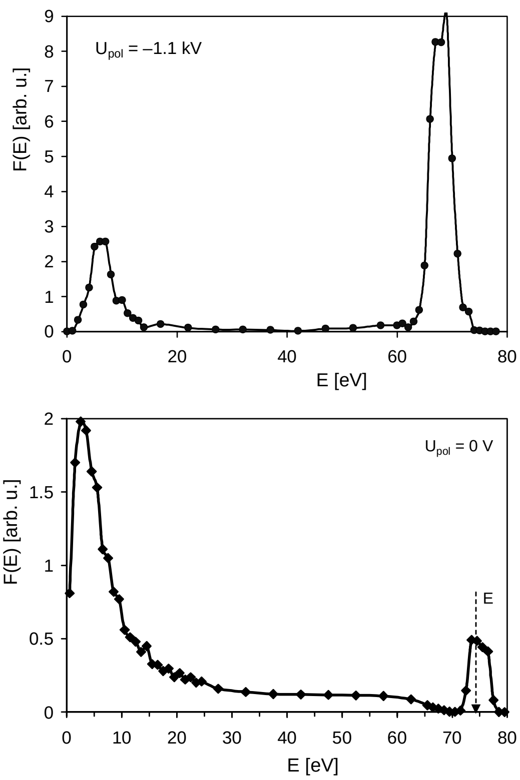

Fig. 8. Energetic spectra of secondary electrons in the field induced secondary electron emission.

pike, which is related to the primary electrons. The shift in the direction of energies lower than E_p (primary electron energy) has been noticed. The effect can be seen in Fig. 8. The change in the primary pike position in the energetic spectrum in the figure can be related to the reduction in the number of elastically reflected electrons from the emitter surface. This means that the majority of the electrons are subjected to the energy reduction (below E_p) and this occurs at the surface zone of ITO.

4. Conclusions

Oxide layers of the ITO type deposited on a glass substrate create the metal–insulator–semiconductor system, where metal is the field electrode, the insulator is glass and the semiconductor is the ITO layer. ITO, in spite of its wide forbidden energy band, shows quite a good conductance. It has been found that such a system under the influence of a high applied voltage emits electrons through the ITO layer into the surrounding vacuum. We call it the electric field induced electron emission and we investigated the emitted electrons from the point of view of their energy. We used an electron multiplier in order to make an analysis of the amplitude spectrum created by the emitted electrons.

The analysis of the amplitude spectra revealed that:

– the total number of recorded pulses and thus the electron emission intensity increase with the voltage applied to the system;

– for lower applied voltages $U_{\rm pol}$ (≤ 1 kV) 1 Gaussian is quite sufficient to approximate the experimental spectrum. So, one can conclude that in this region of applied voltage, the electron energy rising occurs directly due to the applied electric field. It is a proportional region;

– For higher applied voltage $U_{\rm pol}$ (≥ 1 kV) in order to obtain a good coincidence one has to use 2 Gaussians, the second Gaussian has been found to be responsible for electrons of higher energies than the first one. The electrons can be created and accelerated during the avalanche process. In this range of applied voltage emission intensity depends indirectly on the applied voltage. It is an exponential region;

– In the case of high applied voltage and simultaneous illumination of the sample in order to obtain coincidence with the experimental spectrum one should use 3 Gaussians. This means that in this case the additional low-energy electrons appear;

– The mean amplitude of recorded spectrum (amplitude for the maximum of spectrum) shifts in the direction of the smaller amplitudes with the rise of the applied voltage $U_{\rm pol}$;

– Reduction of the mean amplitude of the spectrum is connected with the increase of the total number of pulses, that is, with the electron emission intensity into vacuum;

– Filed induced emission phenomena indicate hysteresis effects.

Wide band gap, degenerate thin oxide films should be considered as semiconductors with a non-parabolic conduction band [14]. A shift of the mean amplitude of the spectrum and the hysteresis effect can be explained in a similar manner as in the Gunn effect, that is, on the basis of the non-parabolic (two-valley) model of a semiconductor band [2, 14]. The drop in the electron energy according to the model occurs during the increase of the applied voltage. A decrease in electron energy with an increase in the applied voltage is related to the shortening of average free distance as a result of electron collisions with other electrons and atoms. These effects lead to reduction of energy whose explanation is similar to the primary pike shift in the secondary electron emission phenomena. The hysteresis effects are connected with the lack of stability due to the fluctuations of the electric field in the surface layer as well as in the glass–ITO interface. The fluctuations occur as a result of creation of the domain structure that diminishes very slowly.

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