ВІСНИК ЛЬВІВ. УН-ТУ VISNYK LVIV UNIV.
Серія фізична. 2007. Вип.40. С.310-317 *Ser.Physic. 2007. N40. P.310-317*

PACS number(s): 79.70.+q

PHENOMENOLOGICAL MODEL OF FIELD INDUCED ELECTRON EMISSION FROM MIS SYSTEM

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The paper contains the results of the research of field induced electron emission from the metal-insulator-semiconductor (MIS) system. Polarized capacitor with the glass as a dielectric and indium-thin oxide (ITO) layers as the conducting plates has been found to be a source of ballistic electrons emitted into vacuum. The final structure of the samples consist of 200 nm ITO as electron emitting layer, $2 \cdot 10^5$ nm glass as dielectric and about 10^3 nm ITO as the field electrode. When negative voltage is applied to the field electrode, it creates an internal field which favors electron emission into vacuum. The studies has been carried out in 10^{-7} hPa vacuum. With increase of biasing voltage the count frequency of pulses grows monotonically. At higher U_{pol} this dependence is exponential. The mean electric field in the dielectric has been estimated to be 10^6 V/m and in ITO layer $E \geq 10^7$V/m. To explain observed electron effects we propose a phenomenological model, with takes into account the possible mechanisms of field induced emission into vacuum. The model is based on the assumption that regions of enhanced and depleted charge carriers appear in the semiconductor layer (ITO) as well as in the glass-ITO interface.

Key words: ITO-glass system, optical and electric properties, electron emission, phenomenological model.

For study the vacuum emission of electrons under influence of field it is possible to use materials known as transparent conducting oxides (TCO). TCO has become widely used in a number of applications [1, 2]. Perhaps the most well-known used TCO materials is tin-doped indium oxide (ITO), which has been in use for over 20 years [3]. If properly doped the oxides indicate a sufficient conductivity to play a role of the upper electrode in MIS systems. Moreover, since they show a high transparence it is possible to illuminate the sample and study the transient photoemission effect. The study results of electric field induced the vacuum emission were presented in the earlier papers e.g. [4, 5]. In the present paper it is attempted to present of the qualitative model of electron phenomena occurring in the surface emitting layer of glass-ITO after creation of the inner electric field. Polarized condenser glass-ITO has been found to be a source of ballistic electrons emitted into vacuum, is as electrons from states below the Fermi level.

The sample for field induced electron emission is MIS like structure: field electrode-glass-semiconductor (indium-thin oxide). Onto a glass substrate the oxide layer is deposited which were admixtured: In_2O:Sn or Sn_2O:Sb (ITO) and is 200 nm thick (Fig. 1). On the opposite side of glass the ITO layer was deposited and it shows a sufficient conductivity to play the role of the field electrode to which the polarizing voltage U_b from 0 do –2kV has been applied. The dielectric thickness was $2\cdot10^{-4}$m and the field electrode-10^{-6}m. Deposition of nanocrystalline indium thin oxide films was performed by reactive dc sputtering technique [6, 7]. The electric conductivity of the examined layers were $2\cdot10^{-4}$ Ωcm [8]. The measurements were performed at the pressure of about $2x10^{-6}$ Pa. The schematic diagram of the apparatus is shown in Fig. 2.

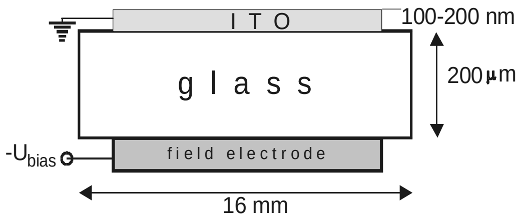

Fig. 1. Shape and size of a sample: ITO, glass substrate and field electrode

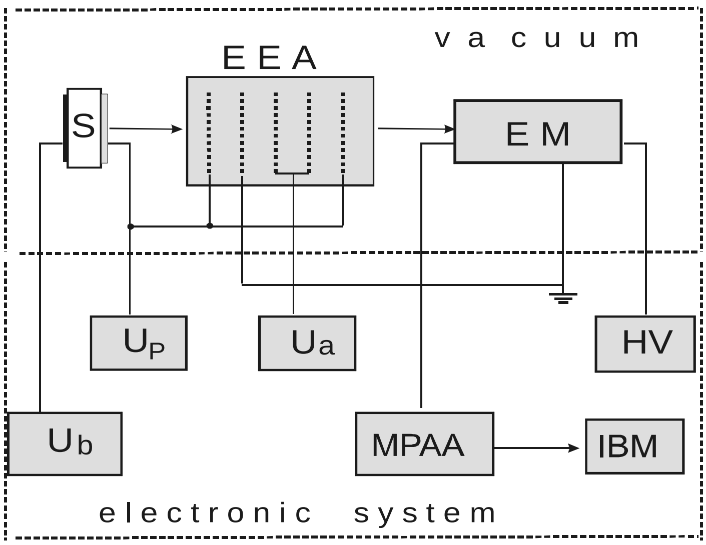

Fig. 2. Experimental arrangement used to study electron vacuum emission from MIS structures

Applying polarizing voltage U_b, from the interval from -2 kV to 0 V, to the field electrode made an internal field, which favored electron emission into vacuum. Appropriate operational conditions for the electron multiplier were received by acceleration of electrons between the emitting film and the multiplier (EM). The electrons accelerated to the energy eU_p create voltage pulses in the multiplier, which are recorded in the multichannel pulse amplitude analyzer (MPAA). The pulses are recorded in channels of the pulse analyzer according to their height, creating so-called voltage pulse amplitude spectrum.

The pulse frequency n as a pulse number recorded during 1 s can be measured and the dependence of frequency n on the voltage U_b can be shown and it can be seen in Fig.3. These dependencies well illustrate the impact of the different voltage U_b intervals on the electron emission phenomena. It should be pointed out that for initial values of U_b (about up to 1 kV) the $n = f(U_b)$ dependence is nearly linear and for voltages above 1 kV shows the exponential behavior. It means that additional effects leading to the increase of the emission efficiency for higher voltages occur. It is also possible to estimate the emitted electron energy using the method of retarding field. It is seen that the spectrum maximum corresponds to the small energies of the range 1 eV, but also are recorded electrons of energies as high as around 10 eV [21].

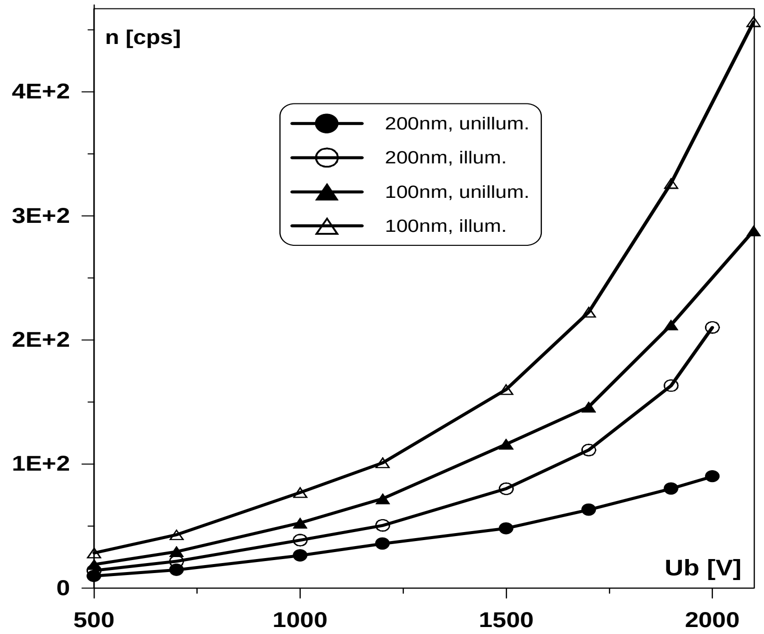

Fig. 3. The pulse frequency as function of the biasing voltage

When a semiconductor (ITO layer) is under influence of the external homogeneous electric field, the free charge carriers are forced to change their spatial distribution. The field do not appear in the entire volume of the semiconductor but in the surface layer of it, where the space charge is accumulated. Initially, at a moderate applied voltage U_b, a relatively homogeneous polarization in the entire volume of semiconductor occurs without clearly formed of enhancement and depletion regions (Fig. 4, *a*). The energy which can obtain electrons under action of these fields are not larger than about kT, that is why the electrons are not able to be emitted into vacuum. When the field increases, the electron energy after their acceleration in the field can obtain larger values than the thermal energy, so E>kT. This additional energy can appear to be sufficient for hot electron to be able to surmount the surface barrier [9, 10].

These effects show Fig. 4b. The work function for indium tin oxides is 4,6 eV [11] and under polarization conditions can be much lower. At high voltages of U_b (more than 1 kV) in semiconductor are created conditions corresponding to E>>kT.

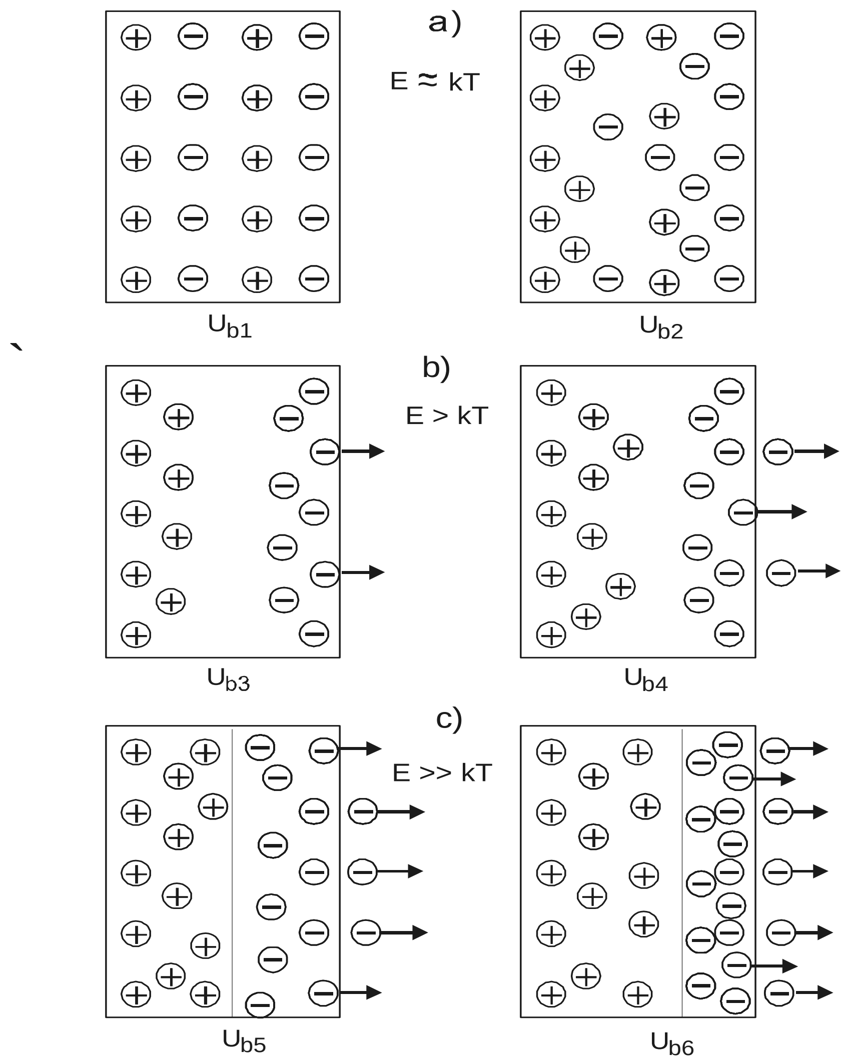

Fig. 4. Schematic illustration of the polarization of ITO layer: creation of enhanced and depleted zones, $U_{b6}>U_{b5}>U_{b4}>U_{b3}>U_{b2}>U_{b1}$

In the ITO layer two separate regions are created: depletion at the glass surface and enhancement at the vacuum boundary. In the depletion zone a mean free path of electrons are enlarged and hot electrons appear, which are able to be emitted into vacuum with energies reaching of few eV. The field intensity at this region of ITO is of the range 10^7 V/m. With the field increasing the enhancement layer is narrower and electron concentration in it is higher: it creates possibility to appear the Zener effect as well as the tunnel effect.

Possibility for electrons to be emitted into vacuum (Fig. 4, *b* and 4, *c* cases) can be described by certain mechanisms mainly based on the bulk structural defects. Examination of thin film surfaces using the tunnel scanning microscope provides the information about the cluster structure with pores, vacancies and channels in the nanometer scale [12, 19]. The similar defects are created in the interface region of glass-oxide. In the ITO materials the main defects are oxygen vacancies and internodes ions of admixtures [13]. The top voids, pores or bulk vacancies can be the source of high localized electric fields. These fields can originate development of avalanche multiplication of electron stream. According to these assumptions four mechanisms of field induced vacuum emission can be distinguished (Fig. 5): the normal emission, the surface defects,. the bulk defects and the full free channel.

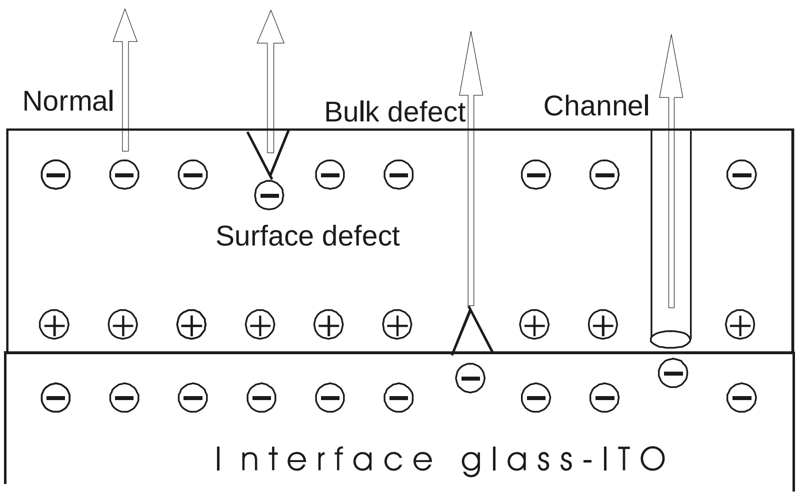

Fig. 5. Probable mechanisms of field induced electron emission phenomenon

The normal emission takes part if electrons from the conduction band achieve in electric field the energies higher than the mean thermal energy (kT). If this excess energy is higher than the work function (lowered by field), then electron can be emitted from the material. The normal emission occurs in the case shown in Fig. 4, *a* as well as in Fig. 4, *b*.

If the defect as a void occurs at the surface, then the field geometry is subjected to disturbance and electrons can be easily extracted by the local fields ($F>10^7$ V/m). According Braunlich et al [14] electrons emitted through that pin hole may gain energy up to 15% of the drive voltage potential eU_b. These effects prevails at the mean values of fields that is as in the case shown in Fig. 4, *b*. The similar role play the defects localized in the glass-ITO interface region. Shape of theirs can be knife-edge or needle point like which injects the electrons. This effect has been already mentioned in papers [15–17] describing electron emission in the vacuum diodes. The oxygen vacancies as the single defects in the electric field can union to form clusters creating the defect channels. The channel can be imagined as a space where electron can be accelerated without the lose of energy. Particularly it is possible when the enhancement zone is so thin, that the tunnel effect can occur. It corresponds to conditions shown in Fig. 4, *c*.

It is proposed the field induced electron emission effect (FIEE) model in which is assumed that as a result of polarization in the ITO layer two zones are created: enhanced and depleted of charge carriers. Due to the field in the depleted zone the electron acceleration to the sufficient high energies is possible. In the enhanced zone the gathering of hot electrons and their emission into vacuum occur. The electron emission can take place from the surface as well as from bulk of ITO layer and from the ITO-glass interface. The model assumes four main mechanisms taking into account the bulk originated electrons emitted into vacuum:

- The normal emission of high energy electrons.
- Emission from vacancies and surface defects.
- Emission from vacancies and bulk defects.
- Emission from full free channels, for instance as a result of avalanche process development.

Thin layers deposited on the dielectric substrate show the cluster structure with pores, vacancies and channels of a nanometer scale [9, 18–20]. This can be proved by the scanning microscope pictures shown for instance in the papers [6, 12, 19]. As a defect precursor can play a role an oxygen vacancy. The structures of this kind enable to create so called full free channels, the mean free path in them is sufficiently long for electron to gain a large energy due to the electric field. The emitted electron energy is of the range 2–3 eV. However, only a small number of electrons in the full free channel can achieve the energy up to 10 eV[5, 21].

The defect joining and creation of the defect channels have been discussed in the 70-ies [15]. Defected channels are responsible for hysteresis effect, we assumed the facts as non repeatability of statistical measurements. Moreover, it has been shown that with the field increase and the measurement duration increase, the samples show the damages induced by eruptive emission pulses causing the yield to the increase even an order of magnitude larger than that in the stationary emission conditions.

The pulses are connected with the formation of defective channels [12], in which the avalanche processes develop. We have found that the emission character before and after eruptive degeneration no more differs than that during the common measurements. We conclude that these effects do not create short circuits which would result non repeatable changes in the samples.

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ФЕНОМЕНОЛОГІЧНА МОДЕЛЬ ЕЛЕКТРОННОЇ ЕМІСІЇ, СТИМУЛЬОВАНОЇ ПОЛЕМ В СИСТЕМІ МЕТАЛ-ДІЕЛЕКТРИК-НАПІВПРОВІДНИК

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Досліджено електронну емісію, стимульовану полем в системах метал–діелектрик–напівпровідник. Польовий конденсатор зі склом як діелектрик та тонкими шарами оксиду індію як провідні пластини використовувався як балістичні електрони, які випромінюються у вакуум. Структура зразків була такою: тонкий шар оксиду індію (200 нм) для електронної емісії, діелектричний шар скла завтовшки 2×10^5 нм та шар оксиду індію ~ 10^3 нм як польовий електрод. За подання від’ємної напруги на польовий електрод створюється внутрішнє поле, яке стимулює електронну емісію у вакуум. Дослідження виконували у вакуумі, що становив 10^{-5} Па. З підвищенням напруги зміщення простежували монотонне зростання частоти імпульсів. За напруг, вищих від U_{pol}, ця залежність має експоненційний характер. Середня величина поля в діелектрику становила 10^6 В/м, в тонких шарах оксиду індію – більше 10^7 В/м. Для пояснення спостережуваних ефектів ми запропонували феноменологічну модель, яка розглядає можливі механізми симульованої полем емісії електронів у вакуум. Модель ґрунтується на припущенні, що і в тонких шарах оксиду індію і в скляному оточенні з’являються області з підвищеним та зниженим вмістом носіїв заряду.

Ключові слова: система тонкий шар оксиду індію-скла, оптичні і електричні властивості, електронна емісія, феноменологічна модель.

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Стаття надійшла до редколегії 29.05.2006
Прийнята до друку 26.02.2007