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Field emission and optical studies of photoelectron transport in GaAs crystal

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Abstract

The photosensitivity of the field emission current from a GaAs crystal with an atomically clean emitting surface has been studied. Measurements of the optical and emission characteristics showed that the quantum yield can reach a magnitude considerably above 100%. A physical mechanism that could possibly lead to this abnormally large quantum yield (for a semiconductor field emitter) is discussed. The feasibility of using a GaAs field emitter as an efficient detection structure is demonstrated.

1. Introduction

Semiconductors are now recognized as field emission materials suitable for use in vacuum electronics. Since the mid-1980s, the interest in vacuum electronics has sharply increased owing to advances in nanofabrication technology: the ability to fabricate micrometre- and submicrometre-sized structures in electronic materials [1]. Vacuum microelectronic devices based on cold-cathode emission can be thought of as micrometre-sized field effect transistor devices.

The basic structure of the field emission cold cathode was proposed over 30 years ago by Spindt [2] and much of the work since then has centred on improving and developing new cathode structures and their fabrication techniques. The well known advantages of field emitters, such as fast rise time, monochromaticity of the electron beam, and high current density, are very important when using a metal field emitter or a semiconducting one as an electron emission source.

In addition to all the advantages of field emitters mentioned above, in studies of the field emission from semiconductors the photosensitivity of the emission current is one of the most attractive aspects.

Early studies of field emission, performed in the 1970s, mainly on CdS, Ge, and Si crystals, reveal that the spectral region of emission photosensitivity coincides with the region of photoconductivity and occurs in the spectral region of fundamental absorption [3, 4].

Measurements of the photofield emission characteristics for semiconductor field emitters have been reported, but the results are extremely contradictory and the investigations were performed rather long ago. The quantum yield was not measured properly in the experimental studies. There was merely a widely held view, based on estimations of the current–voltage (I–V) characteristics [4], that it can reach a magnitude of more than 100%.

Nowadays it is timely and appropriate, in view of the recent rise in practical interest, to readdress the problem experimentally using the modern equipment now available. The present paper concerns the photosensitivity of the field emission current from semi-insulating single-crystal GaAs, including experimental study of the quantum yield. It deals with the investigation of the electron transport through the space-charge region (SCR) of a semiconductor under conditions of field electron emission and illumination.

2. Experimental procedure

Field emitters of dimensions 1 mm × 1 mm × 15 mm, oriented in the ⟨100⟩ crystallographic direction, were made of GaAs single crystals (Fe compensated, of semi-insulating type; $\rho = 10^6\ \Omega$ cm). The tips were formed by chemical etching. The top of each tip, following vacuum degassing and pumping, was cleaned by dc field desorption, step by step, to produce an atomically clean and atomically smooth semiconductor surface, as could be seen using a field emission microscope with resolution of about 20 Å. Cleaning a semiconductor surface by field desorption makes it possible to restore it and to repeat the experiment on a nearly identical surface.

The experimental technique commonly used to investigate the field emission properties of semiconductors consists in measuring the field emission current I as a function of the total voltage V applied between the cold cathode and the anode. The value of the photoresponse (i.e. the difference ΔI between the current in the dark, I_D, and that under illumination, I_L) was measured at different temperatures and anode voltages.

The geometrical disposition of the maximum photoresponse region was determined using a narrow light probe (0.08 mm). A simplified diagram of the scheme used for the measurements is shown as figure 1. The illumination of the semiconductor emitter was performed using a helium–neon laser with $\lambda = 0.63\ \mu$m (1) while measuring the quantum yield of the field emitter.

The incident light beam can be extended with the help of the telescopic objective lens consisting of two co-focusing lenses (2 and 3); then it falls, as a parallel beam, on a slit (4) which is located at double the focal length from the converging lens (5) placed in front of the optical window (6).

In this way, any required tip area can be illuminated by the real optical image of the slit which was used as the light probe, provided that the luminous flux falls on the tip in the direction perpendicular to its length. In this case the width of the slit's optical image is equal to the slit's real width, which can be controlled using the scale of its micrometer screw. It is possible to scan the emitter using the light probe by means of the swinging mechanism of the collecting lens (5). The light probe position and the shadow image of the emitter are observed, with an enlargement factor equal to 100, on the flat screen (8). This screen is placed at the distance of the real optical image of the emitter. Flat sapphire windows (6) were used to provide the illumination of the emitter (13) over a wide spectral region. The anode pin (16) is connected to a conducting film evaporated onto the inner glass walls of the vacuum tube to avoid electrostatic charging.

To determine the value of the quantum yield for the tips of the gallium arsenide, the photoresponse ΔI was measured experimentally. The light flux density was calculated taking

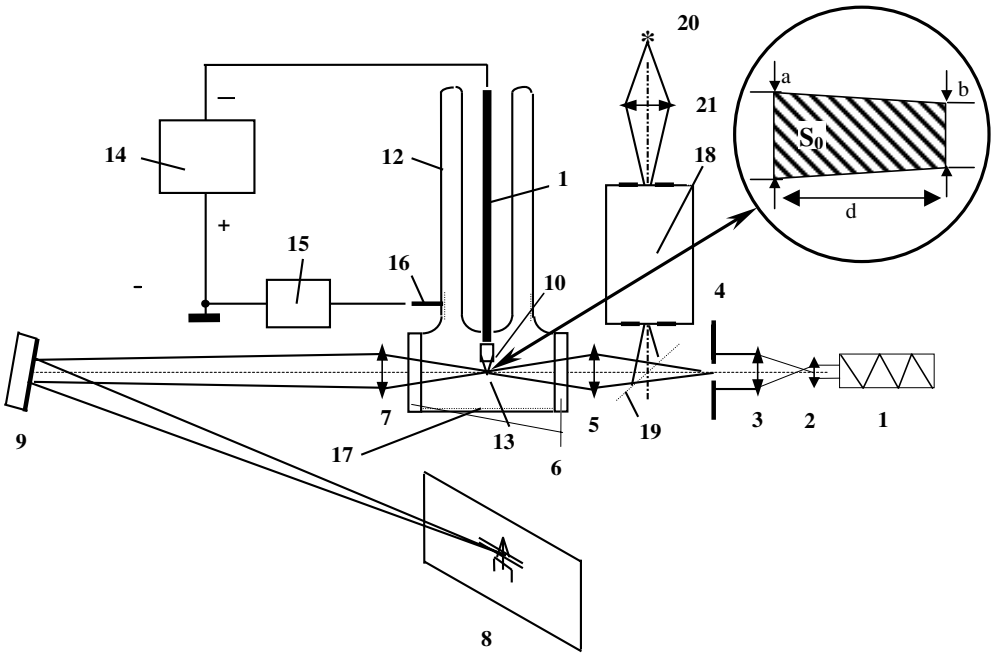

Figure 1. The general scheme used for optical and emission measurements. 1—helium–neon laser; 2, 3—two-element beam collimator; 4—entrance slit; 5—converging lens; 6—optical sapphire windows; 7—collecting lens; 8—flat screen; 9—mirror; 10—screwed metal cylinder; 11—Mo pin; 12—cryogenic tube; 13—semiconductor emitter; 14—source of voltage: high-voltage rectifier; 15—amplifier; 16—Mo pin connected to conducting film; 17—anode; 18—monochromator; 19—mirror; 20—filament lamp; 21—collecting lens.

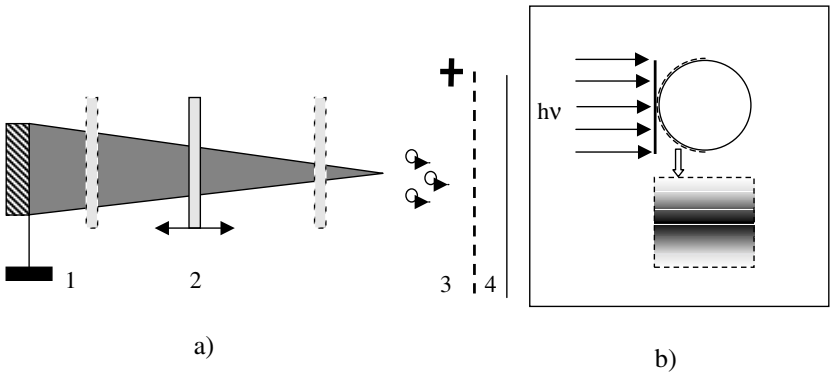

Figure 2. Simplified schemes for light probe illumination: (a) the light probe moving along the emitter; (b) an absorption-active surface and the lighting distribution on the emitter lateral surface.

into consideration the laser power and illuminated area of a tip. Figure 2 shows the simplified scheme used for the field emitter illumination with the help of the light probe achieved while measuring the I–V characteristics.

The optical spectral characteristics of the field emission current were studied to find the spectral region of the field emitter photosensitivity. The illumination of the semiconductor

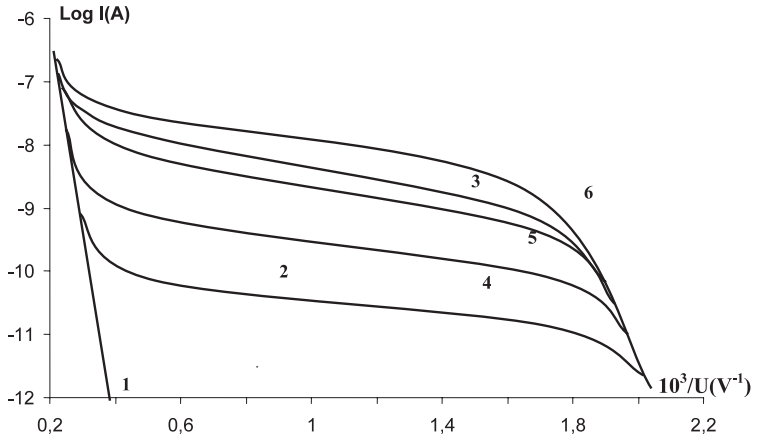

Figure 3. I–V characteristics of the GaAs field emitter (total illumination): 1—dark, 77 K; 2—dark 300 K; 3—dark 373 K; 4—1 under illumination $L = L_{fix}$; 5—2 under illumination $L = L_{fix}$; 6—3 under illumination $L = L_{fix}$.

emitter in these experiments was performed through the same sapphire window (6) of the vacuum electronic device with the help of a monochromator of 'MDR-3' type (18). The calibrated thermoelement placed near the exit slit of the monochromator was used to record the incident light flux.

3. Results

The field emission from a GaAs crystal following etching of a sample and pumping is unstable and no photosensitivity of the emission current is usually observed. Cleaning of the emitter surface by field desorption results in stabilization of the emission current and the appearance of the thermosensitivity and photosensitivity (figure 3). The dark current depends on both the temperature and the anode voltage (see the I–V characteristics 1, 2, and 3). We note that the region of 'saturation' of the I–V characteristic for this high-resistivity semiconductor at 77 K is below 10^{-12} A, and at 77 K only a region of sharp increase of the field emission current is observed (1 in figure 3). It may be seen in figure 3 that a great current increase—up to 10^4 times—is observed under illumination.

Figure 4 shows that the value of the photoresponse ΔI significantly depends on the emitter temperature and the electric field intensity: the effect becomes considerable stronger as both above values increase.

It is very important to estimate the real value of the quantum yield Y for the field detection structure accurately. It has been calculated in the following way. The quantum yield is determined as

$$Y = \frac{N_e}{N_{ph}}, \tag{1}$$

where N_e and N_{ph} are the numbers of photoelectrons and photons, respectively. These values were calculated for the time unit.

N_e can be written as

$$N_e = \frac{\Delta I}{q_e} = \frac{I_L - I_D - I_B}{q_e}, \tag{2}$$

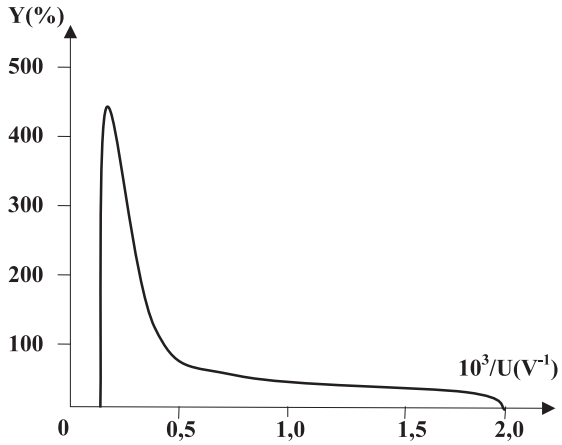

Figure 4. The field dependence of the quantum yield.

where q_e is the electron charge, I_L is the maximum magnitude of the field emission current under illumination when the light probe is localized at the emitter, I_D is the field emission current in the dark, I_B is the light background in the glass vacuum tube connected to an illuminated patch. The magnitude I_B is measured when the light probe is removed from the tip, although the light still passes through the experimental vacuum tube. All measurements mentioned above were performed with a fixed anode voltage.

N_{ph} can be written as

$$N_{ph} = \frac{J_0 S_0 \lambda}{hc}, \tag{3}$$

where J_0 is the luminous flux density, S_0 is the tip area under illumination (it is shown in figure 1), h is the Planck constant, c is the velocity of light, λ is the wavelength of the laser used: laser type 'LGN-109' with $\lambda = 0.63$ μm and power $W = 1$ mW.

The luminous flux density is calculated as $J_0 = \frac{W}{S}K$, where W is the light power, S is the cross-section of the light beam, K is the correction factor describing the light power dissipation due to reflection and absorption in both the lens system and the experimental vacuum tube. For the optical scheme shown in figure 1 the correction factor is estimated as $K = 0.4 \pm 0.1$. It was measured experimentally with help of a photodiode of 'FD-2' type: $K = I_0/I$, where I_0 is the photocurrent measured immediately after the laser exit, while I is measured after the light passes through the lens system (2, 3, 5 in figure 1) and the optical window (6), provided that the photodiode is placed at the field emitter position (13).

The tip area illuminated by the light probe is approximated from the expression $S_0 = \frac{1}{2}(a + b)d$ with allowance made for the conical tip shape (figure 1).

The quantum yield Y as found from the ratio (1) depends strongly on the strength of the electric field. Our results show that the Y can reach a magnitude that is considerably above 100% at high electric fields. This can be seen in figure 4 for the different regions of the I–V characteristics presented in figure 3. We should note that the quantum yield for the GaAs field emission cathode is in reality higher than the value 1, which was calculated from the expression (1) due to miscalculation connected with the tip shape approximation; that is, a real active absorbing surface of a tip is smaller than the approximated one, as is shown in figure 2(a). In addition, the error caused by the irregular light distribution at the emitter absorbing surface (see figure 2(b)) also leads to an increase in the magnitude of the quantum yield, as shown in figure 4. It can be seen in figure 2(b) that the absorbing area and, correspondingly, the absorbed

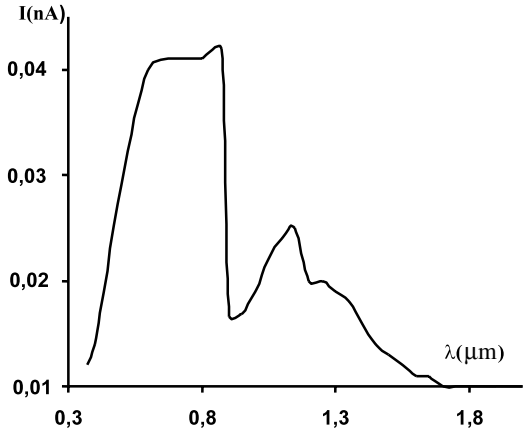

Figure 5. The spectral distribution of the emission current photosensitivity for GaAs.

light power, leading to the emission increase, is lower in the experiment than the one used in our calculation. Therefore, the quantum yield increases on taking into account both of these experimental errors.

Our results show (figure 4) the operating mode in which the field emitter can be used, in principle, as an efficient radiation sensor.

The spectral distribution of the field emission photosensitivity, measured with the help of the ordinary technique using a monochromator, is shown in figure 5. One can see that the spectral range of the emission photosensitivity shifts towards the long-wavelength spectral region (in comparison with the fundamental absorption edge of the crystal) rather considerably: for instance, in the spectral region near $\lambda = 1.1$ μm the photoresponse of the emission current accounts for 30% of the maximum photosensitivity.

4. Discussion

The electron field emission from semiconductors depends on the external electric field, the crystal volume parameters, as well as the electronic structure of the emitting surface. The I–V characteristics (figure 3) can be divided into three regions. At low fields they are straight lines, as in the case of a metal field emitter [5]. The escape of electrons from the SCR due to tunnelling through the external potential barrier is fully compensated for by their influx from the bulk. In this operating mode, no photosensitivity of the emission current is observed.

The electric field increase leads to a potential barrier thickness decrease and hence to an increase in the transparency coefficient. The tunnelling current increases. To compensate for the electron escape from the SCR the bulk current has to increase. However, this process depends on volume parameters, and, in the particular case of GaAs crystal, the field dependence of the electron drift velocity through the GaAs sample has a saturation region [6]. Therefore, after the saturation current is achieved, the influx of electrons from the bulk cannot compensate for their disappearance. This leads to a reduction in the SCR full charge and to violation of the external field screening conditions. The electric field penetrates deeply into the semiconductor volume. A saturation region appears in the I–V characteristics. Any increase in the charge carrier concentration leads to increase in the emission current in this operating mode, provided that the photoresponse depends on the external field intensity.

Common opinion [5] holds that at higher voltage the electric field heats the electron gas, and Zener ionization and impact multiplication of carriers takes place. This leads to an increase

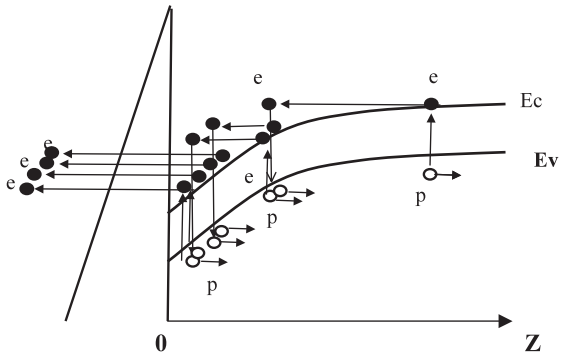

Figure 6. A schematic electron energy diagram of a high-resistivity field emitter.

in the carrier concentration in the conduction band that, in turn, causes a sharp increase in the emission current (the so-called third region of the I–V characteristic). Such field dependence of the dark current is observed for the GaAs crystal (figure 3). Computer simulation of kinetic processes near the semiconductor surface, performed in [7], shows that this increase in the emission current for the GaAs crystal corresponds to strong penetration of the external field into the crystal volume at a field strength of 4×10^7 V cm^{-1}. A full review of early works concerning the field emission from semiconductors can be found in [5], section 8.

Now we consider a mechanism that could possibly lead to the abnormally large value of the quantum yield (for photofield emission cathodes in comparison with the photocathodes currently used). The photoelectrons created due to the light absorption in the bulk of a semiconductor drift to the emitting surface (figure 6). At low values of the external fields, the main contribution to the emission photoresponse is due to the near-thermalized electrons from the bottom of the conduction band. In this case ΔI observed in an experiment depends on the photoconductivity $\Delta\sigma$ which can be written as $\Delta\sigma = e(\Delta n\,\mu_n + \Delta p\,\mu_p)$, where e is the electron charge, Δn and Δp are the differences between the concentrations of electrons and holes, respectively, in the dark and under illumination, and μ_n and μ_p are the electronic and hole mobility.

With increasing field strength, another process also starts to contribute to the current, namely, transport of quasiballistic photoelectrons with increased kinetic energy, as is shown in [8]. The tunnelling probability is governed by the transparency coefficient $D(p_z)$, where p_z is the electron momentum component perpendicular to the surface. $D(p_z)$ rises as the photoelectrons take on increased kinetic energy. This results in ΔI increasing even for a constant value of the carrier concentration n.

The electron kinetic energy produced by an internal potential drop in the GaAs semi-insulating crystal is believed to exceed the impact ionization threshold in gallium arsenide. The voltage drop along the emitter as measured by means of the retarding potential technique reaches several hundreds of volts. The 'active' absorbing area is situated at a distance of several hundreds of microns from the top of the tip. Hence the generation of new electron–hole pairs is very likely to occur, as in the case of the dark current described above. At collision with crystal lattice atoms, they lose part of their energy acquired in the field, increasing the carrier concentration by means of impact ionization. It is these new electron–hole pairs that, together with the hot photoelectrons, lead to the very high value of the quantum yield. The relation between the electron free path and lifetime in the near-surface potential well with respect to emission also defines the emission regime.

In the field emission study of high-resistivity semiconductors at low temperatures, the question of the origin of the emitted electrons arises, since the conductive band is empty when no electric field is applied to the crystal surface. Therefore, the dark current could be caused by either the emission from the valence band or the free electrons generated as a result of the field penetration into the semiconductor. It has been shown, in particular in [4], that strong Zener ionization takes place in a high-resistivity semiconductor under field emission conditions.

Carrier generation by light, depending on the semiconductor parameters, may also lead to voltage redistribution and to a displacement of the voltage from the emitter, as was observed by Apker and Taft for the CdS crystal as early as 1952. If the field emission is limited by the barrier penetrability and the rate of carrier generation is higher than that of their escape, an accumulation of carriers will occur. The equilibrium state can be achieved by voltage redistribution. The voltage increase across the vacuum gap results in an emission increase due to the higher barrier penetrability. We should note that in any case the final explanation can only be based on an electron energy distribution study.

Our results show that the quantum yield increases with strengthening electric field (figure 4) and so the magnitude of Y under appropriate field conditions is above 100%. We note that so great a quantum yield is impossible, in principle, for the photocathodes currently used.

It is known that in the one-dimensional case the tunnelling current for a certain energy E is given by the product of the transmission function, that is determined by the rate of tunnelling of electrons through the surface–vacuum barrier, and the supply function, that is given by the rate of supply of electrons of a given energy from within the crystal to the surface barrier.

Therefore, a decrease in the recombination probability of the photoelectrons, associated with the surface state density at the emitting surface and their occupation [9] as well as with the features of near-surface quantum wells [10], leads to an increase in the magnitude of Y—that is, in the number of electrons which enter the vacuum through the semiconductor–vacuum potential barrier due to the quantum mechanical effect of tunnelling. It is reasonable to expect the electronic structure of the emitting crystal surface to have an influence on the quantum yield magnitude.

We can conclude that the value of the quantum yield for a field emitter depends mainly on three factors: (a) the photon absorption in the bulk of a semiconductor and the photoelectron generation; (b) the transport conditions for the photoelectrons moving in the bulk to the emitting surface; and (c) generation–recombination processes at the semiconductor–vacuum interface. It is obvious that to improve the quantum yield of a field detection structure in practice, it is necessary to change both the bulk and surface parameters of a semiconductor field emitter associated with the three above-mentioned factors.

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