FIELD EMISSION FROM SEMICONDUCTOR POINT ARRAYS

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Abstract - The paper reports on the fabrication of multi-point arrays from Ge, Si, and GaAs by means of optimization of photolithographic method. The origin of uncontrollable centres of emission on the surface has been investigated by means of SEM, AE- and SIM-spectroscopy. An investigation of the electron energy distribution from the probing zone of cathode surface at different operating modes of the cathode have shown the "broadening" of distribution with the increase of current take-off level. By measuring the frequency characteristics of the field emission current fluctuations it has been found that the noise power spectrum is well approximated by the I/f function in the low frequency range.

The history of the multi-point field-emission photocathodes fabrication /1 - 5/ has shown the nonuniform distribution of emission centers on the cathode surface to be the main obstacle on the way of their wide application. It is known that the geometrical uniformity of the tip matrix largely determines the emission uniformity. However, even the structures with high degree of geometrical uniformity often showed the presence of uncontrollable emission centers not connected with the obtained structure; therefore, to fabricate field-emission photocathodes with stable uniform emission and high quantum efficiency it is necessary to find out the nature of such emission centers and the ways of thier removal.

The photolithographic method with a subsequent chemical etching /1, 3, 4/ is one of the promising ways to fabricate field-emission arrays. In /6/ we proposed a procedure for optimization of this method by using up-to-date achievements in microelectronic technology that permitted to fabricate matrices of semiconductor points of a given height (5 - 30 mu) and configuration with the point density of more than 7.5×10^5 cm^{-2}. Figure 1 shows the main stages of fabrication of such a matrix. A clean monocrystalline plate is coated with a tantalum film by means of magnetron sputtering. After that, with the help of projection photolithography, a matrix of Ta disks is produced (10 - 15 mu in diameter and 0.1 - 0.2 mu in thickness) which are then oxida-

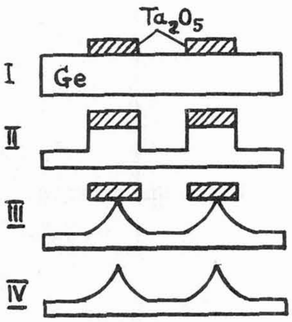


Fig. 1 - The main stages of fabrication of semiconductor multi-point arrays.

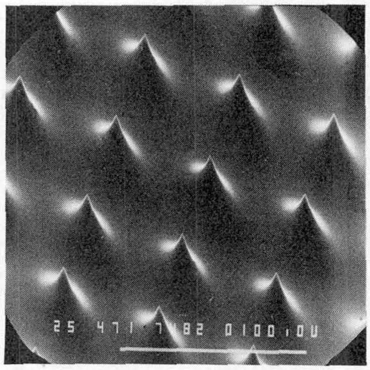


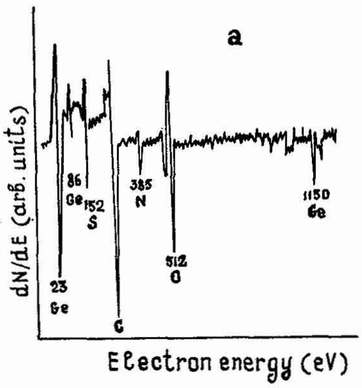
Fig. 2 - Scanning electron micrograph of field-emission array on p-Ge (3 Ohm·cm).

ted to Ta_2O_5 (Stage I). Further on (Stage II), using ion-plasma etching, columns of a certain height protected with Ta_2O_5 masks are fabricated which are additionally oxidated to create point structures (Stage III). Finally, the Ta_2O_5 mask is removed by a high-frequency discharge in the argon medium (Stage IV). Figure 2 demonstrates a typical micrograph of the obtained structure. To refine and select some technological operations a character of the topology change of the semiconductor surface was investigated using a scanning electron microscope. The Auger electron and secondary ion mass spectroscopic analyses were used to determine the concentration and chemical composition of the impurities on the surface and the subsurface areas of the semiconductor. Used were monocrystalline plates of different specific resistivity made of Ge(III), Si(III), and GaAs(III) (2 - 3 cm^2 in area and 0.3-0.8 mm in thickness).

The AES spectrum of the original Ge plate shows the following peaks: C with energy 272 eV, N with energy 385 eV, and S with energy 152 eV. As a result of preliminary purification of Ge substrates in a peroxide-ammonia solution the intensity of C and S peaks considerably decreases (though does not disappear completely). It was established that the greatest contamination of the surface when using photolithographic method was brought about by the operation of photoresist removal in monoethanolamine. In the corresponding AES spectra (Fig. 3b) there is a presence of O peak (512 eV), of highly-intensive C peak (272 eV) as well as admixtures of nitrogen and fluorine. That is why the removal of the protection mask was carried out with the use of ion purification by a high-frequency discharge in the argon medium. The AES spectrum of the treated substrate (Fig. 3c) has shown a considerable reduction of impurities on its surface.

When carrying out a layer-by-layer analysis of the chemical composition, the plate of a semiconductor was etched for 2 - 5 min to several dozens of Å.

Distribution curves of the element concentration according to the thickness of the plate were built as the Auger-peak intensity function of sputtering



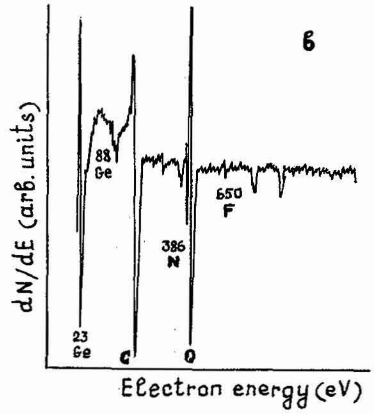
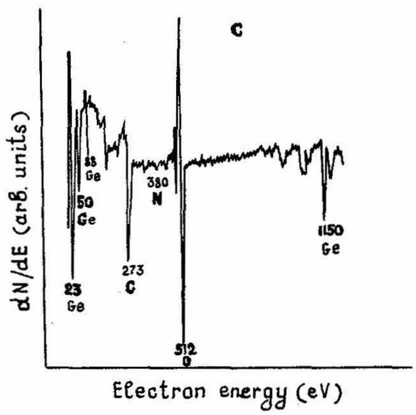


Fig. 3 - AES spectra of Ge plate after the treatment.



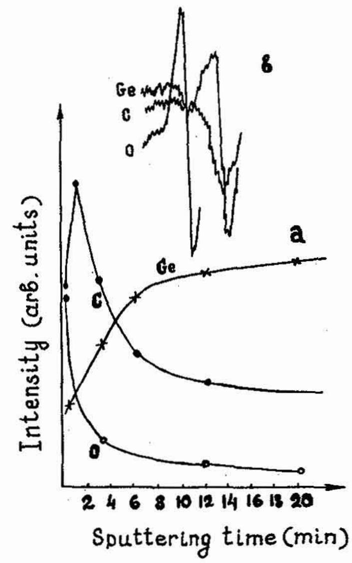


Fig. 4 - Concentration profiles of elements in the subsurface layer of Ge plate after ion-plasma etching (a) and AES spectrum of its surface (b).

time. Figure 4a presents the data on the element distribution by thickness in a Ge plate after ion-plasma treatment and the AES spectrum of its surface (Fig. 4b). Peak intensities of Ge (1110 eV), C (272 eV), and O (490 eV) are compared. The results indicate that accumulation of C and O is observed both on the surface and in the bulk of the semiconductor. The appearance of impurity aggregates on the semiconductor surface causes a potential relief on it that explains the spot-like character of emission. As it turned out these impurities contain in a great amount the atoms of alkali metals, the majority of the former being of the volumetric origin of their own. The typi-

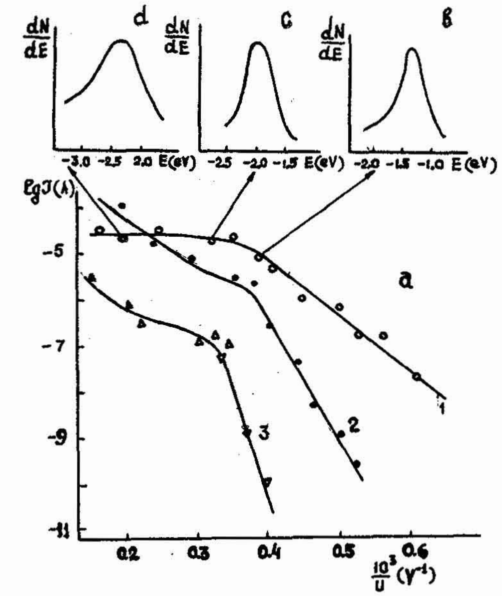


Fig. 5 - a) Current-voltage characteristics of semiconductor multi-point arrays taken at T = 300 K after ion-plasma treatment:
1) p-Ge (40 Ohm·cm);
2) p-Si (40 Ohm·cm);
3) p-GaAs (30 Ohm·cm).
b), c), and d) corresponding curves of field-emission electron energy distribution ($E_F = 0$).

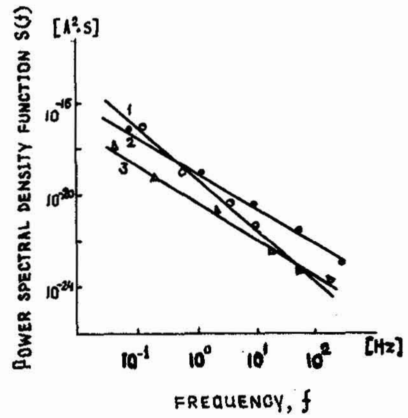


Fig. 6 - Field-emission current fluctuation spectra from semiconductor multi-point arrays taken at T = 300 K in Fowler-Nordheim region of the current-voltage characteristics at emission current $J = 7.5 \times 10^{6}$ A:
1) p-Ge (40 Ohm·cm);
2) p-Si (40 Ohm·cm);
3) p-GaAs (30 Ohm·cm).

cal composition of impurities on the Ge cathode introduced during the treatment consists of C, S, F, N and their amount could be reduced by an appropriate selection of the technological process and operating modes. Further on we compared the emission properties of multi-point arrays obtained in order to find out if there was any dependence between the impurity contents on the surface and the appearance of uncontrollable centers of emission. A measuring cell apart from the cathode contained a closely located (100-400 mu) anode-screen that permitted to observe the emission centers distribution on the whole cathode area. A preliminary ion treatment of the cathode surface would bring to a more uniform start of the tip operation but even under these conditions one would observe disappearance or birth of separate uncontrollable centers of emission which manifested themselves by the appearance of several unstable bright spots on the background of the less luminous region. Current-voltage characteristics of emission current were taken in the darkness when cooling with liquid nitrogen and at room temperature (Fig. 5). It was found out that the dark current of field-emission photocathodes changed depending on their specific resistance as well as on the preliminary treatment of the substrate surface. At room temperature, all cathodes showed sufficiently high dark current in the range 10^{-8} - 5 x 10^{-5} A. When cooling with liquid nitrogen, the level of dark current decreased and amounted, for example, for a cathode made of p-Ge (30 Ohm cm) to (1 - 2)x10^{-11} A and to 8x10^{-10}A with and without ion treatment, respectively. A sharp increase of dark current was observed with the increase of impurity concentration on the semiconductor surface (up to 10^{-4} A). The increase of the dark current took place also during long opeartion of the cathode at constant voltage and room temperature. Current-voltage characteristics of the total current from the whole emitting cathode surface for p-type specimens had a typical nonlinear form (Fig. 5) and looked like earlier ones /1 - 5/. Similar current-voltage characteristics were obtained for local (up to 100 Å in diameter) areas of cathode surface as well as when carrying out energy analysis of electrones. Measuring of the field-electron energy distribution was carried out under three operating modes of cathode: the beginning of the saturation part (Fig. 5b), the middle of it (Fig. 5c) and the part of current-voltage characteristics transient to multiplication region of the current carrier (Fig. 5d). As is seen from the above-mentioned results the energy distribution curves have one maximum and the total width of the energy distribution at half a height rises from 0.6 eV (Fig. 5b) to 2.2 eV (Fig. 5d) with the increase of the total emission current.

When taking off high current (about several hundreds of muA) the formation of emission centers was observed on a p-Ge emitter (0.2 Ohm cm) outside the tip structure and their examination with the help of SEM made it possible to find out new structures - small islands (50 - 300 mu in diameter) resembling craters. An AES analysis of three typical regions was made: that of small island, regular (point) structure and a region of the surface without structure (i.e., outside the cathode), in the latter there was no emission center. The AES analysis of the small islands showed an increased content of K and also the presence of C, N, and O peaks and the absence of K in the neighbouring regions that proved a spotted character of the impurity distribution. Due to low sensitivity of the AES method to Na, the latter was found by means of SIMS. The greatest aggregates of alkali metal impurities leading to the local decrease of the work function were observed on submicron defects of a Ge plate. In such a case the change in intensity of electrical field should bring about the change in the rate of alkali metal diffusion to the emitter surface from its volume. This fact may be connected with the repeated appearance of the pictures of uncontrollable centers at different anode voltages.

The spectra of current fluctuations in the low-frequency region were investigated in order to select optimal technological working conditions and analyze the stability of operation of the multi-point cathode. The liquid chemical etching in fabricating the structures gives a much larger scattering in the radii of points than the ion plasma one and leads to a greater geometrical nonuniformity which manifests itself in a considerable increase of the noise level. The preliminary ion cleaning of the plate surface by a high-frequency discharge brought about the decrease of the noise level. The measurements have shown that the I/f - noise is the main component of the field-emission current fluctuations in the Fowler-Nordheim region of the current-voltage characteristics. The dependence of spectral density function on the frequency S(f) for cathodes of Ge, Si, and GaAs (Fig. 6, curves 1, 2, 3) is well approximated by the I/f^{γ} function that affords for the application of a statistic model / 7 / to describe fluctuation which relates the noise power with the average number of emitting centers. The appearance of uncontrollable emission centers leads to oscilations in the emission current and to a qualitative change in the shape of the S(f) curve. In the region of saturation of current-voltage characteristics where the emission current is mainly determined by the rate of generation of minority carriers the noise level practically drops down to the shot noise level, and S(f) acquires the shape which is close to that of the Lorentz spectrum. The last circumstance is very important in the application of semiconductor multipoint field-emission photocathodes as threshold infra-red detectors.

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