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Formation of a field emission array for the efficient conversion of electron energy into X-ray radiation for the maskless X-ray lithography

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Abstract

This paper discusses the technological prospects for creating a field emitter array for the efficient conversion of electron energy to X-ray radiation in a portable X-ray source. Fabrication process of a field emission array and X-ray transparent beryllium membrane is proposed. Three-dimensional model of field emission array combined with beryllium membrane was created in COMSOL Multiphysics. Dependence of X-ray conversion coefficient vs. voltage between a field-emission array and beryllium membrane was calculated and dependence of electron energy vs. electron beam radius was obtained as a result of electron transport simulation.

Introduction

Nowadays various fields of science and technology are in need of miniature X-ray sources that would have low energy consumption, small work preparation time, and most importantly, would have a high conversion coefficient of X-ray radiation. In practical applications, the use of a field emission arrays in X-ray sources is very attractive alternative to the traditional thermionic cathodes. In the previous work [1], a plateau of the conversion coefficient was shown experimentally, which is in the 1-3 keV range of energy and these results are sufficiently consistent with theoretical concepts.

One of the main advantages of using field emission cathodes is a narrow electron beam, which allows obtaining small focal spots on the target with sufficient intensity. As a source of electrons, either a single blade-type field emission cathode or an array of needle-type field emitters can be used in order to achieve high total value of the emission current [2-3].

Materials and methods

In this paper, we propose a method for creating a field emission arrays. Silicon wafers doped with phosphorus (n-type conductivity) with (100) crystallographic orientation and 150 mm in diameter were used. Wafers were oxidized in wet O_2 ambient (thickness of SiO_2 layer was 0.3 μm), Si_3N_4 layer was deposited as a masking layer (thickness of Si_3N_4 layer was 0.13 μm) after oxidation. Photolithography was performed on wafers to form oxide-nitride caps for the following etching process. The next stage was creation of specific curved profile of the silicon pillars. Such curved pillars were made using plasma-chemical etching in a mixture of SF_6 and O_2 with an anisotropy coefficient of 2.5. Final oxidation process in dry O_2 ambient transformed silicon pillars into sharp tips with nanoscale radius of curvature (3 nm). After that SiO_2 layer along with Si_3N_4 layer were removed from the substrate.

Beryllium membrane was created using the following fabrication process. Thinned silicon wafer was oxidized and thin (20 nm) TiN film was deposited on SiO_2 as a protective layer. After that thick beryllium layer was deposited, 30 nm of a TiN layer is deposited on beryllium, and finally polycrystalline Si layer (450 nm) was deposited on the top of the substrate. Bosch process was used to form deep trenches on the front side of the substrate. Final structure was obtained after silicon micrograss disposal and etching of SiO_2 and Si_3N_4 layers.

BrewerBOND 305 process of wafer bonding may be used to meet the conditions for correct functioning of the whole X-ray source: alignment accuracy at least 1 μm and absence of conductivity between the membrane and field emission array. Alignment process includes the following stages: deposition of BrewerBOND 305 layer (10-15 μm) on a wafer with field emission array; photolithography on a wafer with field emission array and BrewerBOND 305 layer; preparation of wafer with beryllium membrane and final alignment of wafers.

The efficiency of electron energy conversion into X-ray energy is characterizes by conversion coefficient η. This parameter can be calculated using the following equation:

$$\eta = \frac{E_{ph}}{E_e} * \frac{2\pi}{\Omega_{ph}} = \frac{h * c * I_{ph} * \tau_{ph} * 2\pi}{\lambda_{ph} * U_{ca} * I_{f-e} * \tau_e * \Omega_{ph}} \tag{1}$$

where E_{ph} is total generated X-ray photon energy, E_e is falling electrons energy, Ω_{ph} is solid angle of X-ray detector ($2.6*10^{-3}$ str), h is the Planck's constant, c is the speed of light in vacuum, Iph is an intensity of X-ray radiation ($3.3*10^{16}$ photon/s), τ_{ph} is a duration of X-ray generation pulse (10^{-13} s) [4], λph is an X-ray photon wavelength for beryllium membrane (11.4 nm), U_{ca} is a voltage between field-emission array and beryllium anode, I_{f-e} is a field emission current from one silicon cathode, τ_{ph} is a duration of electron emission pulse (0.001 s).

Three-dimensional model of a field emission array with beryllium membrane was created in COMSOL Multiphysics and full simulation of electron transport from field emitters to target (membrane) was performed to obtain dependence of the electron beam radius on electron energy and X-ray distribution (fig. 1).

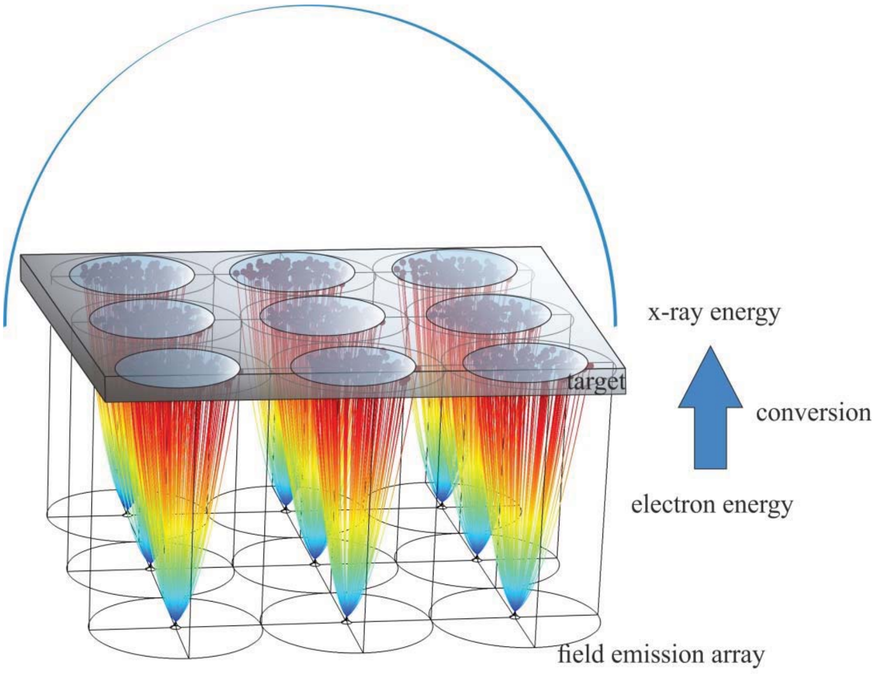

Fig. 1: Three-dimensional model of field emission array with beryllium membrane for conversion of electron energy into X-ray radiation. Color lines show trajectories of emitted electrons.

Results and discussion

The energy of X-ray radiation depends on the energy of the electrons which fall on the membrane. In this paper the distribution of X-ray radiation and dependence of electron energy vs. electron beam radius were obtained as a results of simulation of electron transport in COMSOL Multiphysics (fig. 2). Current–voltage characteristics of the array of silicon field emitters obtained at a distance of 300 μm between the anode and field emission array on the experimental set-up (fig. 3a) [5]. In addition conversion coefficient η was calculated using the equation (1) for the variation of U_{ca} from 2.2 to 3.35 kV (fig. 3b). Values below 2.2 kV were eliminated due to a very low value of emission current in this range.

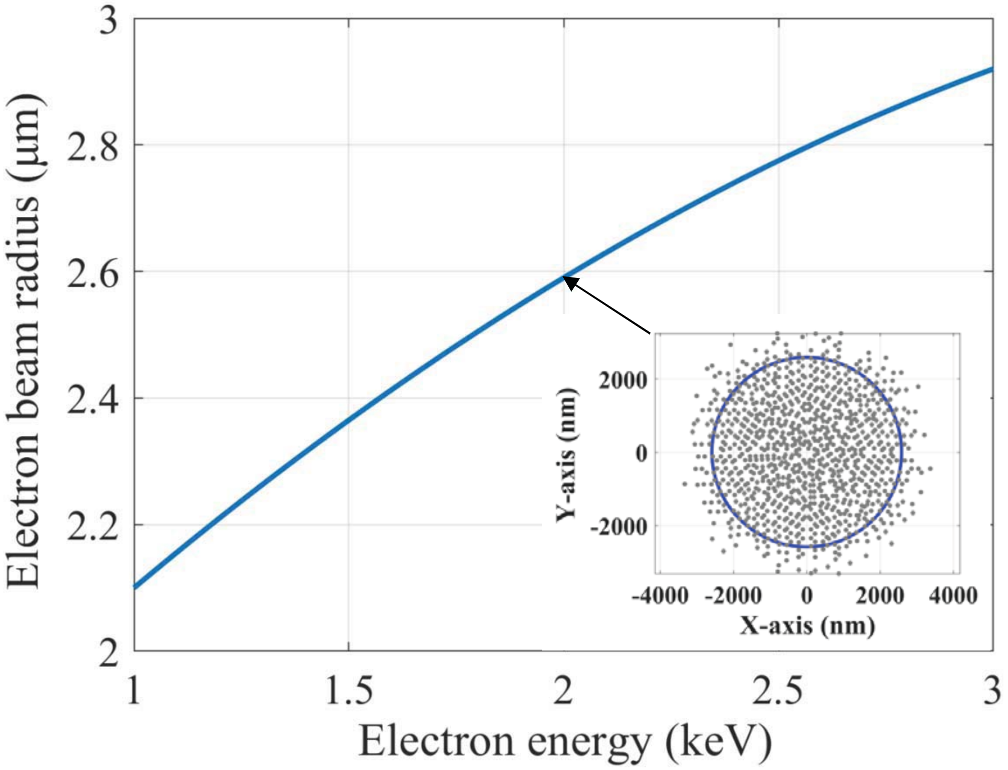

Fig. 2: Dependence of the electron beam radius on electron energy and X-ray distribution.

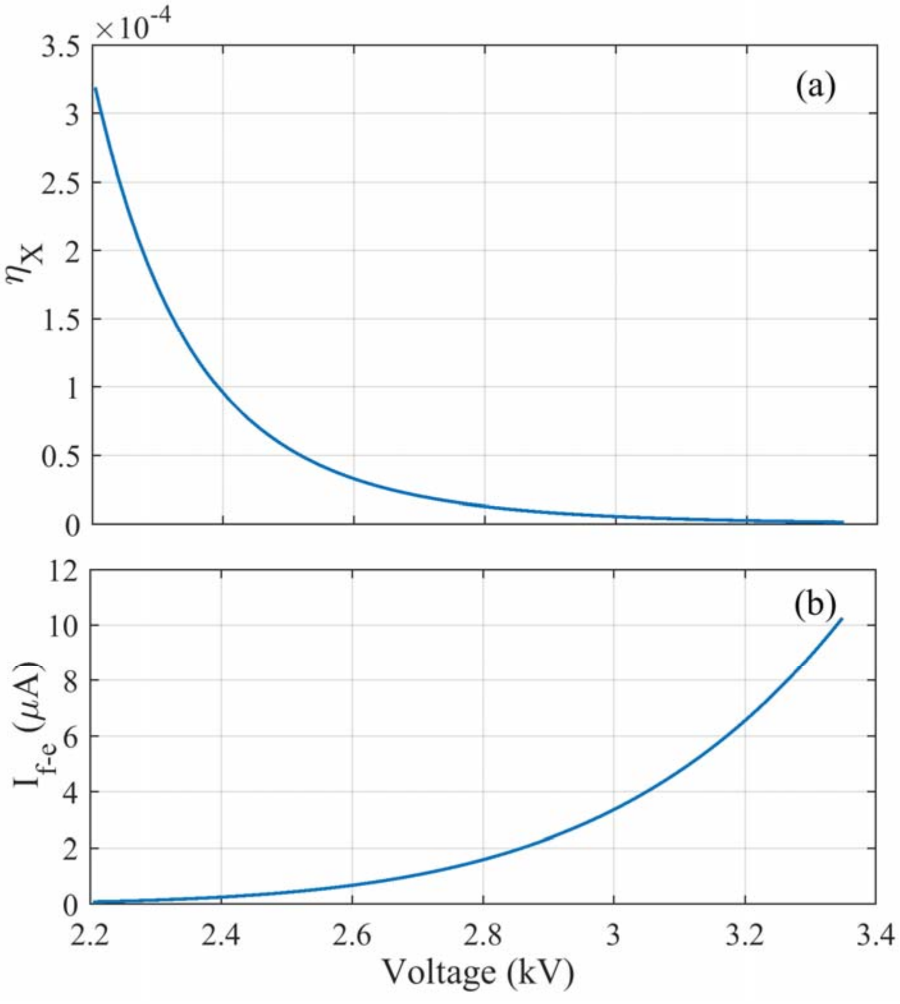

Fig. 3: (a) Dependence of the conversion coefficient on voltage between field emission array and anode membrane; (b) Dependence of the field emission current on voltage between field emission array and anode membrane.

Summary

Fabrication process of field emission array combined with beryllium membrane for the efficient conversion of electron energy into X-ray radiation for the maskless X-ray lithography was proposed. Three-dimensional model of a field emission array with beryllium membrane was created in COMSOL Multiphysics and full simulation of electron transport from field emitters was performed. Conversion coefficient η was calculated for the various values of U_{ca}.

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