Paper

Fabrication and properties of the field emission array with self-alignment gate electrode

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Abstract — A new method for the fabrication of field emission arrays (FEA) based on bulk/surface silicon micromachining and diamond-like-carbon (DLC) coating was developed. A matrix of self-aligned electron field emitters is formed in silicon by mean anisotropic etching in alkali solution of the front silicon film through micro holes opened in silicon oxide layer. The field emission of the fabricated emitter tips is enhanced by a diamond-like-carbon film formed by chemical vapor deposition on the microtips. Back side contacts are formed by metal patterning. Detailed Raman, Auger and TEM investigations of the deposited DLC films (nanocrystalline diamond smaller than 10 nm) will be presented. In this paper we discuss the problems related to the development of field emission arrays technology. We also demonstrate examples of devices fabricated according to those technologies.

Keywords — field emission array, field emission display, diamond-like-carbon layers emission, silicon micromachining, self- alignment technology.

1. Introduction

The most characteristic feature of today electronic market is a very strong development of portable equipment sector. The demand for pocket systems as games, cellular phones, palm-top computers and advanced measurements systems increases remarkably. All this application require low power consumption and new visualization systems. Standard LCD technology however, which dominates in production of the integrated circuits and systems, has some serious limitations. The most promising solution of this fundamental problem seems to be employment of the field emission display (FED). FED is one of the principal candidates for future flat screen displays. Its key attraction is the ability to deliver high quality (in terms of brightness, colour, viewing angle) images with relatively low power consumption.

Investigations on the new materials with negative electron affinity and new technologies allowed to build field emitters which can be operated at low voltage and in very poor vacuum with very high current density. Costs and the device performance are the most important issues influencing the industrial applicability of the FE-arrays (FEA) devices.

2. Theory

In typical solutions, single emitter cells consist of a microtip located in a hollow, with the tip apex surrounded by a gate electrode (Fig. 1). The electron emission current (I) from the tip describe Fowler-Nordheim relation:

$$\frac{I}{V^2} = \frac{\alpha\, a\, \beta^2}{\phi} \exp\left(\frac{-\mathrm{b}\phi^{\frac{3}{2}}}{\beta V}\right), \quad E = \beta \cdot V\,,$$

where: ϕ – work function, β – enhancement factor, a – emission area, E – electric field strength, V – voltage, I – emission current, α, b – constants.

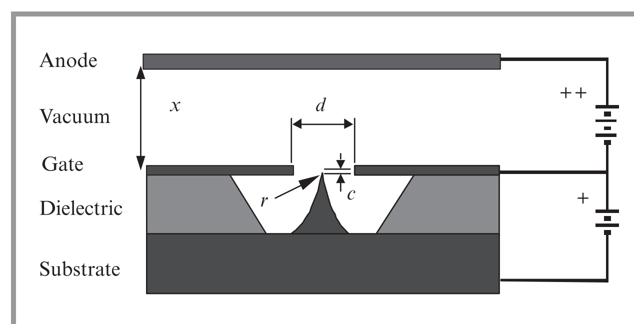

Fig. 1. Typical single field emitter cell.

The enhancement factor (β) depends strongly on the tip radius (r) and on the gate opening diameter (d). The processing sequence has to be optimized to obtain very sharp tip, small diameter of the gate opening and very good uniformity of the structure geometry. A good alignment of the tip due to the gate opening is particularly important.

3. Fabrication

The micromachining fabrication process was based on a sequence of deposition, lithography, and dry/wet etching processes. Double side polished, <100> oriented, $4 \div 5$ Ωcm n-type silicon wafers were used as a starting material. First, the bottom, 400 nm thermal silicon oxide layer was created, then low stress $0.5 \div 1.0$ μm SiO_xN_y film was deposited using PECVD technique. The emitter shape was defined in first lithography step. The tip location and the central gate opening are formed in the same lithography step,

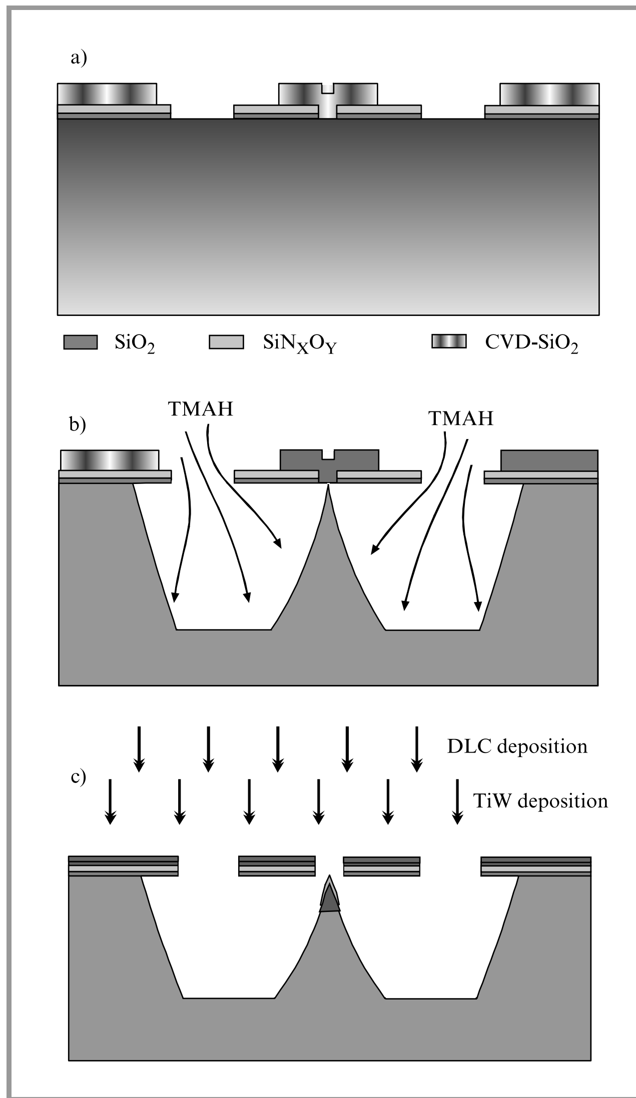

Fig. 2. Field emitter array cell fabrication by silicon micromachining; (a) ÷ (c) explanation in the text.

thus ensuring perfect self-alignment of the gate and the tip (Fig. 2a).

Low stress silicon oxide layer was deposited and in a second lithography step to enable access to silicon surface. A matrix of self-aligned electron field emitters is formed in silicon by mean anisotropic etching in alkali solution of the front silicon film through micro holes opened in silicon oxide layer (Fig. 2b). Then was deposited TiW metal film by means of magnetron sputtering technique followed by CVD DLC film deposition (Fig. 2c). This double layer coating provides a conductive gate electrode. The DLC film was also deposited at the apex of the tip.

4. Results and discussion

Figures 3 and 4 show the SEM microscopy photographs of the fabricated emitter arrays.

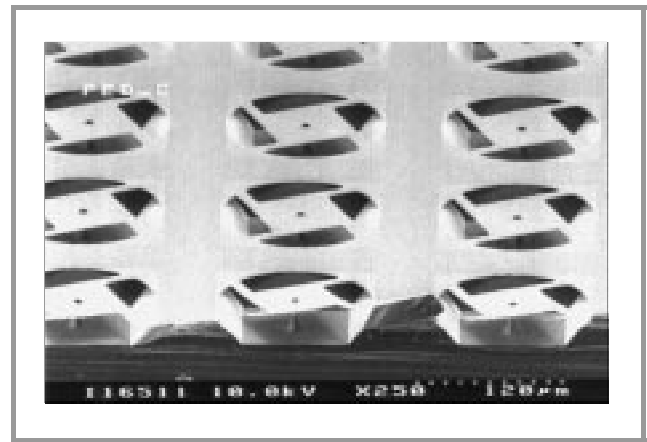

Fig. 3. Field emitter array fabricated using silicon micromachining technique.

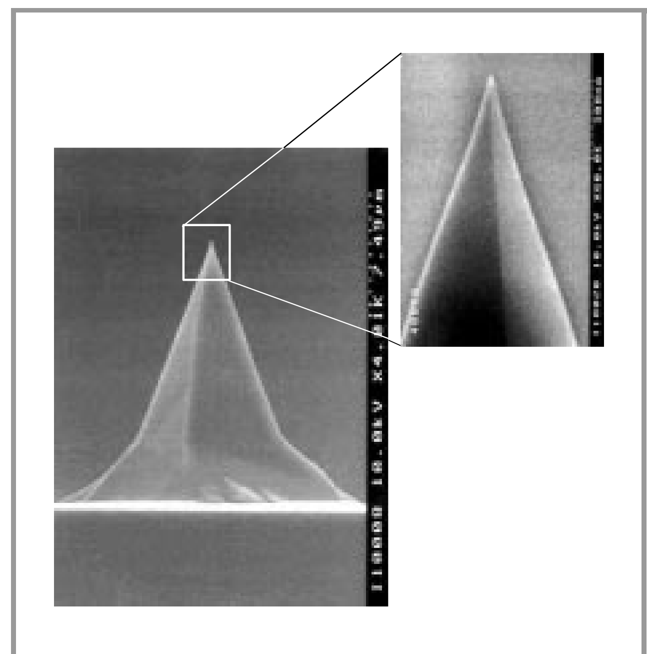

Fig. 4. SEM photographs of the silicon tip with apex region enlarged. Visible very good sharpness of the tip.

Uniformity of the fabricated microtips was very good. The tips were sharp, with curvature radius below 50 nm. Additional sharpening by means of thermal oxidation yields a tips with radius in the range of 20 nm or better. Emission performance of the fabricated tip array was estimate by measuring the emission current for samples 10×10 mm big with 2800 tips.

Experimental results of the field emission measurements regarding F-N behavior and long term stability of the electron current for the different emitter structures including unique characteristics of uncoated and DLC coated silicon tips will be presented and discussed.

4.1. Characterization of the TEM microscopy

We have used a Philips CM200 STA with LaB_6- cathode and CCD- camera (with resolution 1024 × 1024 pixel), 200 kV acceleration voltage, condenser aperture 100 μm, objective aperture 50 μm. The TEM investigations do not show the presence of nanocrystallites below 10 nm (Fig. 5).

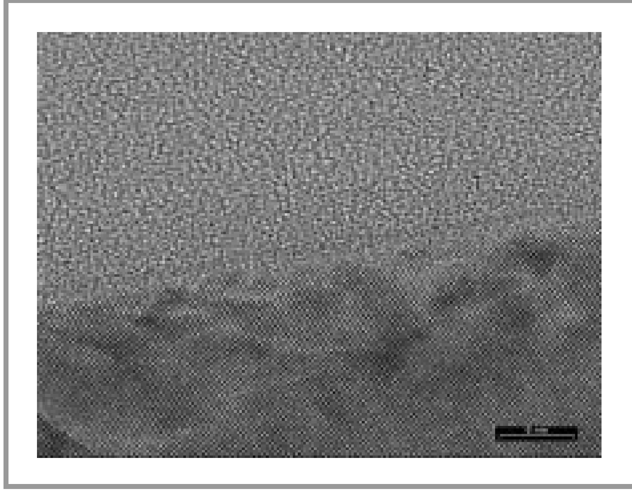

Fig. 5. TEM analysis – nanocrystalites below 10 nm could not be seen.

4.2. Characterization of the Raman spectra

Basic structural investigations of the carbon DLC were done by micro-Raman spectroscopy. The Raman spectroscopy proved the presence for the nanocrystallites. The Raman spectrum of DLC layer (Fig. 6) shows a sharp peak at about 1340 cm^{-1} which is usually referred to as diamond peak. The second peak emerges at 1600 cm^{-1} and is referred to as graphite peak. Given the relative sensitivities of the Raman technique to diamond and graphite at the wavelength used, it can be estimated that the film contains a few percent

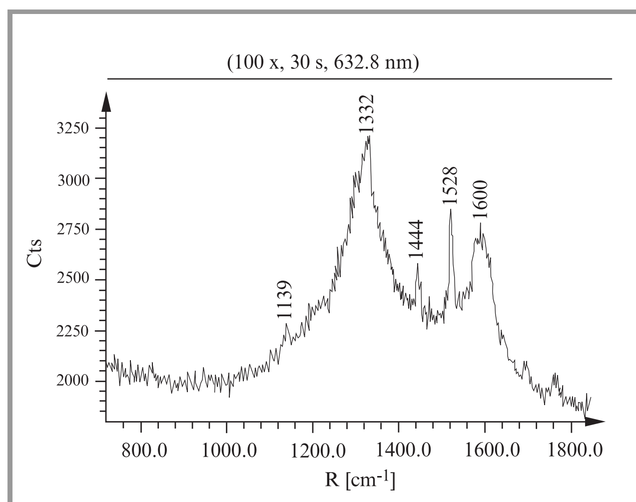

Fig. 6. Raman spectra of the DLC film deposited on the FE-sources.

graphite. The full width at half-maximum of the 1332 cm^{-1} peak can be attributed to a very small grain size (below 10 nm) of the diamond nanocrystals.

4.3. Measurements

The emitter array sample was placed in a vacuum chamber. The chamber was pumped down below $1 \cdot 10^{-6}$ Torr. Next, the I-V characteristics were measured using 610C Keithley electrometer. Two types of arrays were evaluated, coated with DLC film and silicon structures without DLC coating. Results of the measurements are shown in Fig. 7. The relatively low threshold voltage equal to 150 V was observed

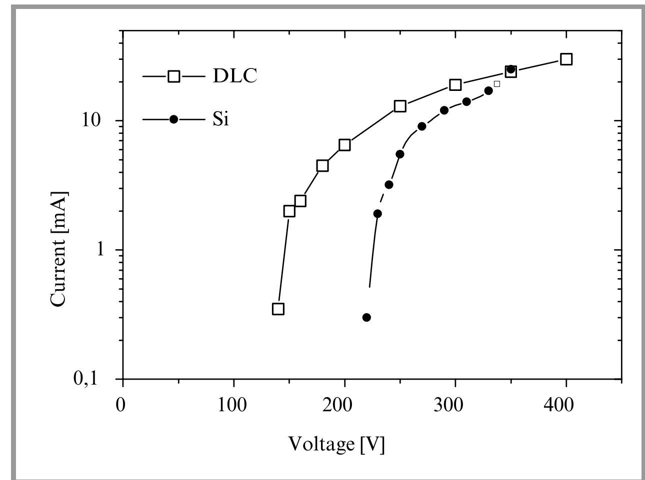

Fig. 7. F-N characteristics of the coated and uncoated silicon emitter arrays.

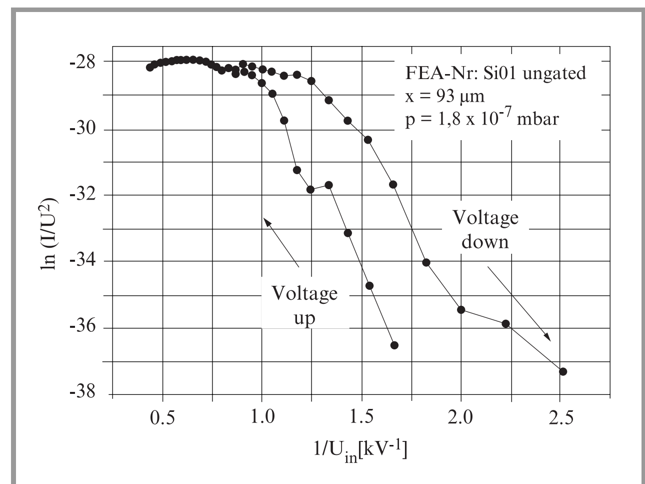

Fig. 8. The hysteresis of the F-N plot was observed (ion sputtering of the tip).

for DLC coated tips, while for uncoated Si tips threshold above 200 V was noted. The maximum current 11 μA per tip was measured for DLC coated structures, while for uncoated Si tips the maximum current was 9 μA per tip. It is evident that the DLC coating has a considerable influence

on the emission efficiency. A hysteresis of the F-N plot was observed most probably due to ion sputtering of the tip (Fig. 8).

5. Summary

A new silicon micromachining method for fabrication of field emission arrays was developed. The process is simple and allows for self-aligned gate electrode formation. The DLC coated silicon tip array was fabricated using the developed technique. The developed technology could be useful for a production very wide range of field emitter arrays applications such as flat panel displays, high frequency devices, field emission electron guns, field emission cathodes, low energy electron microscope, field emission diodes and field emission triodes. Further investigation of the work function and long time emission stability of the emitter arrays has to be performed.

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