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MICRO ELECTRON FIELD EMITTER ARRAY WITH FOCUS LENSES FOR MULTI-ELECTRON BEAM LITHOGRAPHY

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ABSTRACT

We report on the fabrication and characterization of a monolithic electron field emitter device with focus lenses for multi-electron beam lithography and high density nano data storage. An array of individually addressable emitters was formed on oxidized etch pits of an SOI (Silicon on Insulator) wafer. Si active layer of the SOI with gate hole array that self-aligned with the emitters was used as a common gate electrode. An array of cylindrical holes formed on the Si base of the SOI was used as a common lens electrode. The emitters, gate and lens array components are isolated each other by 2 μm-thick thermal SiO_2 layers.

For a single Pt emitter with gate hole of 2 μm diameter and anode voltage V_{anod}=0.7 kV, the emission current started at a gate voltage Vg=90 V and reached to 1.2 μA current and 0.84 mW beam power at V_g=300 V. The emission current was found to be stable with a fluctuation smaller than 10 %/h. The emitter-gate and emitter-lens leak currents were found to be less then 1% compared with emission current. The focusing characteristic of the device was experimentally confirmed. A simulation work has shown that the beam with emission cone angle within 15° can be focused at a spot of 40 nm at a lens voltage, V_{lens}= -6 V.

INTRODUCTION

Researches on electron field emission devices (FED) or cold cathodes have been carried out for a long time because of their potential applications in microwave power amplifier, flat panel display, electron beam analysis tools, microscopy, electron beam lithography, etc. [1]. Typically, electrons are emitted from the FED device in a cone angle of 30° or larger. For many practical applications, collimation and focusing of the beam are very critical. Several approaches for integrated electrostatic lens systems have been developed, such as planar lenses (coplanar type) [2-3], and coaxial type focusing lens [4].

To achieve a goal of high throughput multi-electron beam lithography [5-11] or high density data storage [12-13] based on electron emission, we need electron beam array with smallest possible focusing and acceptable long-term emission stability. Several attempts were paid to study a hybrid structure of Scanning Tunneling Microscopy tip or microfabricated emitter aligned with a miniature electron optical column [5-8]. Another approach was developed using MEMS technology to fabricate multi electrostatic lens layers [14]. To improve long-term emission stability, recently, many studies were done in the investigation of new materials such as metallic carbides, carbon nanotubes, diamond as emitter [15-16].

In this work, we present a device concept, fabrication, emission and focusing characteristics of the micro electron field emitter array with the focus lenses. The device was monolithically fabricated on a conventional SOI wafer with the MEMS process. Several emitter materials such as Mo, Cr, Pt, Boron doped diamond, Carbon nanotubes have been examining. Here, we present the results with Pt, Mo emitters.

CONCEPT OF THE DEVICE AND FABRICATION RESULTS

Concept of the multi electron beam lithography system is shown in Fig. 1. It consists of individually addressable gated emitters and integrated micro electrostatic lenses. The media or wafer can be moved by using a micromachined nano-positioning stage. Such multi beam system can overcome traditional limitations in production rate, and electron-optical complexity. A prediction of sub-50 nm lithography with a 60 wafers/hr throughput rate was analyzed for the mentioned concept [10]. The device structure is schematically depicted in Fig. 2. It consists of individual addressable sharp emitters, gate hole and cylindrical lens array on the SOI wafer. The emitters, gate and lenses components are isolated from each other by thermal SiO_2 layers with 1-2 μm in thickness. In our device, electron beams are expected to be focused at several hundreds μm far way from the device, i.e. the device is not contact with the media.

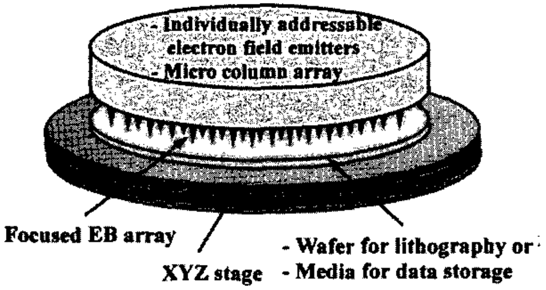


Fig. 1: Concept of the multi-electron beam lithography and nano-data storage system

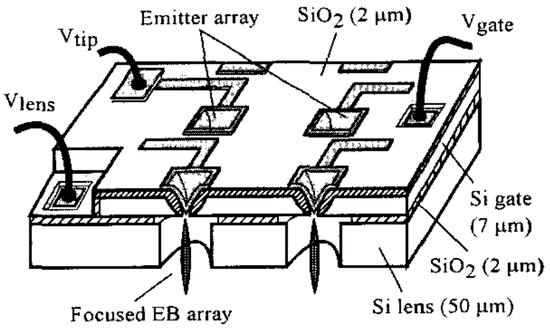


Fig. 2: Schematic structure of the device on SOI wafer

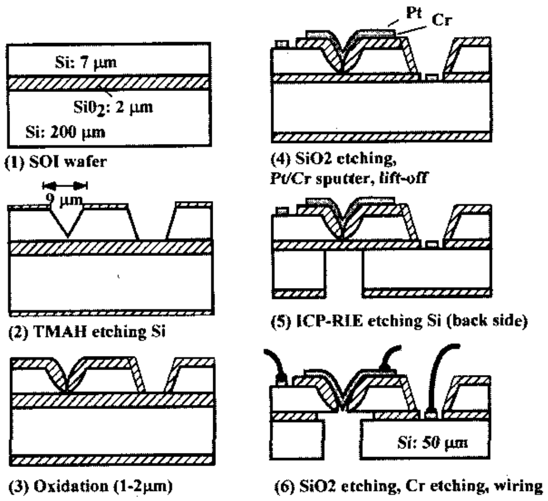
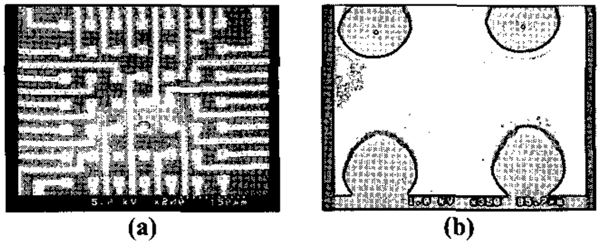


Fig. 3: Fabrication process of the device

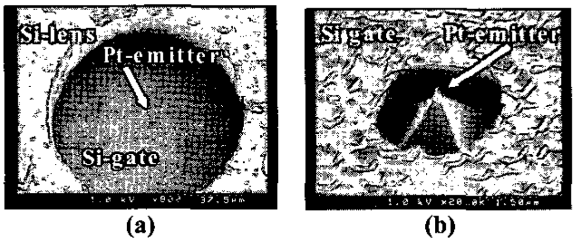
Since the gate hole array can be fabricated in small size and be self-aligned with ultra-sharp emitters, high brightness electron beam array can be field-emitted at a low gate voltage V_g. The emitted electrons can be focused when the voltage applied to the lens V_{lens} is lower than that is applied to the gate electrode V_g. By changing the voltage, incorporating extraction and focusing electrode, the focal length can be changed.

The fabrication process is shown in Fig. 3. We start from the SOI ($Si/SiO_2/Si$) wafer of (7/2/200 μm), (100)-orientation, boron doped, double side polished (step 1). An array of pyramidal etch pit sized of 9 μm was formed on the 7 μm-thick active Si layer by photolithography, SiO_2 patterning and Si wet etching in a TMAH solution (step 2). A contact window for lens electrode was also opened at this step. Next, a thermal SiO_2 layer of 1-2 μm-thick was grown at low temperature [17] (step 3). This oxide layer serves as an isolation of the emitters and the gate. And these oxidized etch pits will serve as molds for forming sharp emitter tips with various materials. Next, Pt/Cr (300/50 nm-thick) or Mo patterns for emitters, gate and lens contact pads were formed by photolithography, metal sputter and lift-off techniques (step 4). Next, a photolithography and Si dry etching at the



(a) (b)

Fig. 4: (a) SEM image of the 7x7 emitter array matrix from the upper side of the device; (b) Lens array with visible gated emitters from the lower side of the device.



(a) (b)

Fig. 5: SEM images of a lens (a) and a close-up view of one gated Pt emitter in the array (b)

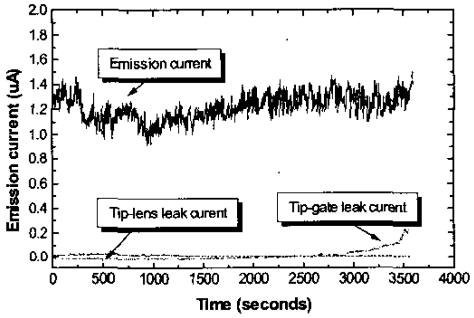


Fig. 6: Emission and tip-gate, tip-lens leak currents of single Pt emitter as a function of time (V_g=300 V, V_{anod}=700 V)

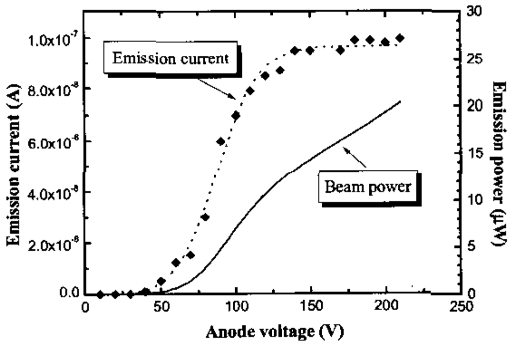
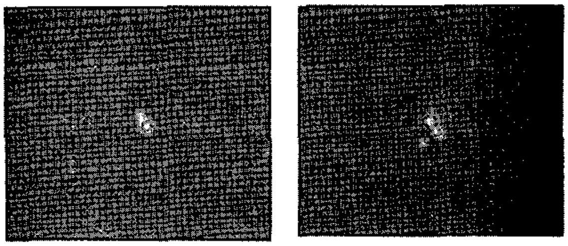
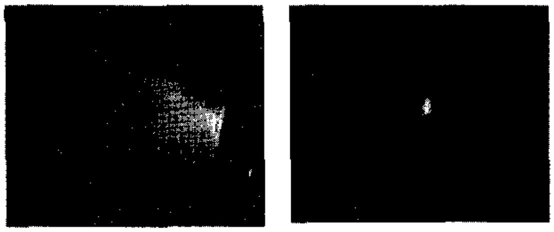


Fig. 7: Emission current and corresponding beam power at V_g=150 V as a function of anode voltage for single Mo emitter.



(a) (b)

Fig. 8: Emission patterns of single Mo emitter at Vg=200 V (a) and Vg=300 V, respectively (Size of main spot ≈500 μm)



(a) (b)

Fig. 9: Emission patterns of one Pt emitter without (a) and with −10 V focusing (b) (Spot diameter ≈200 μm)

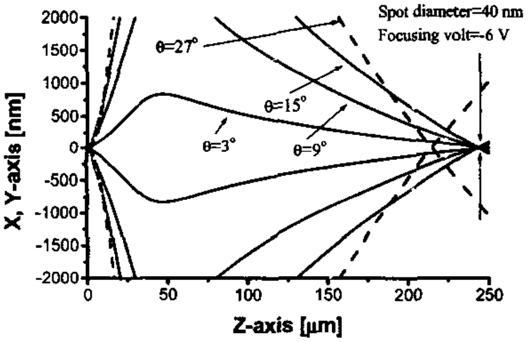


Fig. 10: Simulated focusing result of the device with V_g=100 V, V_{lens}= -6 V

base side were done to form electrostatic lens array with diameters in the range of 40-80 μm and 50 μm-height (step 5). Since the thickness of the Si base was 200 μm, an additional dry etching was used to reduce the thickness of the lens down to 50 μm. Finally, the gate holes were opened by etching the SiO_2 and Cr at the apex of emitter was removed in a Cr etchant to expose the Pt tips (step 6).

Fig. 4a shows SEM image of the 7x7 emitter array matrix with distance tip-to-tip of 60 μm from the upper side of the device. Fig. 4b shows SEM image of the lens array with visible gated emitters looking from the lower side of the device. Fig. 5 shows a close up of the single gated Pt emitter with the integrated lens in the array. As shown in Fig. 5b, a very sharp Pt emitter was formed and self-aligned with the gate hole.

MEASUREMENT AND SIMULATION RESULTS

We characterized the electron emission, emission lifetime as well as focus behavior of one emitter in the array in a vacuum chamber of $3x10^{-7}$ Torr. A Hewlett Packard HP-4155A unit was used to supply bias to the gate, lens and anode and to monitor the emission current. To observe the emission pattern and collect emission current, a glass plate coated with a transparent conducting indium tin oxide (ITO) and phosphor (ZnO, Zn) was used as an anode screen.

For the single Pt emitter, the emission current started at gate voltage (V_g) of 95 V and reached 1.2 μA at V_g=300 V. The emission current was well obeyed the Flowler Norheim law. Single Mo and Cr tip emitted electrons at a threshold voltages of 95 and 120 V, repectively. However, Pt emitter shows a brighter emission current and better stability. Fig. 6 shows the variation with the time of the emission current, tip-gate and tip-lens leak currents of single Pt emitter measured at Vg=300V, Va=700 V. The emission current was found to be stable with a fluctuation smaller than 10%/h. The leak currents of emitter-gate and emitter lens were found to be less than 1% compared to the emission current. Fig. 7 shows the dependence of emission current of single Mo tip at V_g = 150 V and corresponding beam power as a function of anode voltage (V_a). The beam power was defined as the product of the emission current and the corresponding anode voltage. As seen in Fig. 7, for single Mo emitter, the beam power of 18 μW can be achieved at V_g=150 V and V_a=200 V. Pt emitter can yield a beam power of 0.84 mW at Vg=300V, Va=700 V. We expected that the emitted low energy electron beam has enough power to write patterns in lithography and modify bits in a data storage media.

To improve the long-term emission stability, we are also trying to fabricated doped diamond and individual carbon nanotube as a single emitter in the device. The detail of fabrication and emission characteristics of the diamond and CNT will be reported elsewhere. Fig. 8 shows emission pattern of the single Mo tip at Vg=200 and 300 V, respectively. As seen in Fig. 8, the light spot become brighter with increasing the gate voltage. Moreover, beside the the main light spot, there was several other smaller spot. This means that to focus the emitted electron beam, a point electron source using such as nanotube is needed [9].

The focusing characteristic of the device with single Pt tip was experimentally examined. Figs. 9a, b show emission pattern of one beam without and with −10 V focusing, respectively. Diameter of the focused beam 200 μm was observed by the anode screen situated at 1cm above the device. When the focus bias is increased above the optimal value, it over-focuses the electron beam causing it to cross over the optical axis (increases the spot size). The exact beam diameter at the best focus position was not found yet because the breakdown of the emitter during the measurement. The breakdown was happened because the emitter-gate leak current became larger after several hours operation.

We have simulated the focus characteristic of the device as well as the design of the device by using a finite element method. The model was build on the basis of the actual geometry (Fig. 2) and operation voltages of the device as: Vg=100 V, gate opening diameter=1 μm; radius of emitter=10 nm; emitter cone angle=60°; anode-emitter distance 250 μm and V_{anod}= 1kV (4 V/μm); lens diameter=60 μm and lens height=50 μm. Fig. 10 shows trajectory calculation of electron beam with different emission cone angle. The simulated result in Fig. 10 shows that, for V_g=100 V and V_{lens}= -6 V, electron beam can be focused with a focal length of 250 μm. Electrons which emitted from the emitter within 15 degrees emission angle could be well focused with a beam diameter of 40 nm.

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