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Novel photocathodes using vacuum microelectronics technology

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Abstract

A new photocathode called a ''photosensitive field emitter'' has been proposed, and a prototype was fabricated. This new photocathode was realized using a gated Si field emitter tip and an hydrogenated amorphous Si (a-Si:H) p–i–n photodiode. The emission current from the photocathode is proportional to the illumination intensity, and detectable maximum of the illumination intensity was about 4000 $\mu W/cm^2$. The quantum efficiency was about 0.7. Its dynamic range was about 200 times wider than that of the field emitter type photocathode using non-gated field emitter. Moreover, the dark current was suppressed less than 0.1 nA. © 2000 Elsevier Science S.A. All rights reserved.

Keywords: Photocathode; Vacuum microelectronics; Field emitter; Image sensor; Amorphous silicon

1. Introduction

Recently, photocathodes with high effective quantum efficiency has been in demand for super high sensitive imagers, which is used for astronomical observations and a medical science. The conventional photocathodes have been widely used as the photoreceptor for various photoelectric devices, for example, an image intensifier and a photo-multiplier tube. The photocathode has many advantages, such as a low dark current and a fast response time, however, the quantum efficiency (the number of electron emitted from the cathode per incident photon) is quite low. The quantum efficiency of the well-known photocathode made with Sb–K–Na–Cs (S-20 type) has a value of about 0.2 and the poor signal to noise ratio (S/N) of photoelectric devices using this photocathode results from this low value. Moreover, the photocathode is not sensitive to infrared light of longer wavelength (2 μm).

Recently, field emitter arrays (FEAs) have received an increasing interest in many applications, such as flat panel displays [1], high-speed micro-vacuum devices [2], and image pick-up devices [3]. Some experimental results of photosensitive field emitters have been reported [4]. The sensor yields a high dark current level at room temperature, and a low quantum efficiency. In this paper, we present a new photocathode that is fabricated using vacuum microelectronics technology. Advantages of the field emitter type photocathode are high quantum efficiency and low dark current.

2. Device structure

The proposed new photocathode was constructed with a gated n-type Si field emitter tip and an a-Si:H p–i–n photodiode film. The schematic cross-sectional view of this device is shown in Fig. 1. At first, cone-shaped field emitters were fabricated on n-type (100) Si substrate (3 Ω cm) by using reactive ion etching (RIE) and thermal oxidation shaping [5]. The radii of the apex of the emitter is about 40 nm and the 100 tip were integrated in a 1.5×1.5 mm square. Hydrogenated amorphous Si (a-Si:H) photodiode film was deposited on the back side of the n-type substrate. An intrinsic a-Si:H layer (undoped layer) (3 μm) and a p-type a-SiC:H (B-doped hydrogenated amorphous silicon carbide) layer (300 nm) were deposited successively on the back of the Si substrate by using the conventional plasma enhanced chemical vapor phase deposition (PE-CVD) system. Finally, a semi-transparent gold

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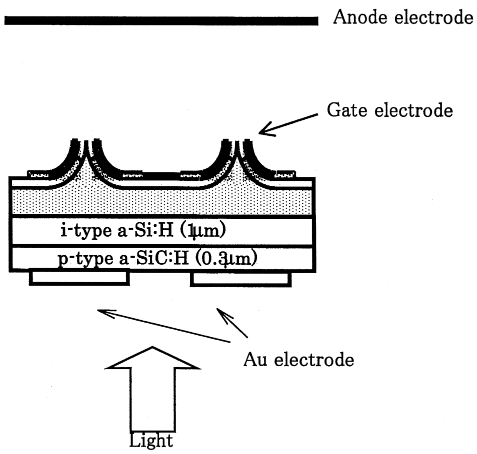

Fig. 1. Schematic cross-sectional view of a proposed photosensitive floating field emitter.

film (20 nm) was sputtered as an electrode. The size of the electrode is about $1.5 \times 1.5\ mm^2$.

3. Basic operation of the non-gated version

The operation of the field emitter type photocathode can be described using the model shown in Fig. 2. This model is made with an n-type Si field emitter and a conventional p–n junction photodiode, which are connected in series.

An operation of the photocathode in a dark condition is described. Schematic diagrams of the potential distribution of the photosensitive field emitter in dark conditions are shown in Fig. 3. The p-type substrate is grounded. At a low anode voltage, there is no emission of electron from the tip of the field emitter. As anode voltage increases and a voltage of the emitter tip exceeds the threshold voltage (V_{th}) (required voltage to be able to tunnel the vacuum barrier), electrons are emitted from the tip (Fig. 3(a)). In the case that a voltage (V_{A1}) larger than V_{th} is applied to the anode electrode, electrons are emitted from the n-type Si tip of emitter and the potential of the n-type tip is increased. To keep charge neutrality, the depletion region at the p–n junction is extended. Electrons are emitted until the voltage of the emitter tip are equal ($V_{A1} - V_{th}$), and the photocathode reach the steady state (Fig. 3(b)). In an equilibrium state, the voltage at the depletion region of the p–n junction is equal to $V_{A1} - V_{th}$. Since the potential difference between the anode and the n-type Si tip is only V_{th} in ideal dark condition, electrons are not emitted from the tip. In reality, since dark current flow through the p–n junction, the electron emission relative to the dark current will be observed. It seems this dark current is quite small compared with that of the p-type photosensitive emitter proposed by Thomas and Nathanson [4]. The dark current of the photosensitive field emitter proposed by us is restricted by the thermally generated electrons in the depletion region of the p–n junction. On the other hand, the dark current of the p-type photosensitive emitter proposed by Thomas and Nathanson is decided by the generation rate of electrons on the surface, because the surface of the tip is depleted. A lot of dangling bonds on the surface of the silicon emitter are existed, since the surface is bare. The generation rate of electrons at the emitter surface is so fast.

Cases when the photosensitive floating field emitter in the steady state are irradiated incident lights is described. Schematic diagrams for the potential distribution of the photosensitive field emitter with the photo-irradiation conditions are shown in Fig. 4. The light irradiation in the depletion region can induce a generation of the electron-hole pairs (Fig. 4(a)). Generated electrons move to the n-type tip and holes are swept to the p-type substrate. The motion of electrons causes the drop of the potential at the floating tip. Then potential difference between the anode and the floated tip increase beyond V_{th}, and electrons are emitted from the floating tip (Fig. 4(b)). As the light irradiation is increased, the potential difference between

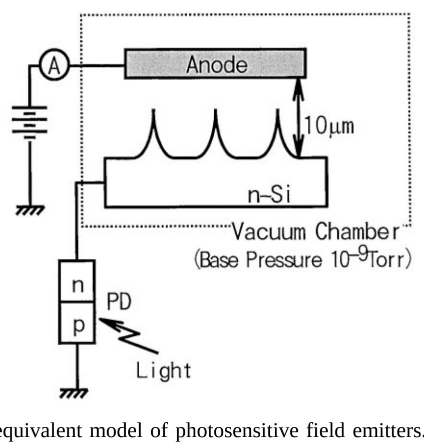

Fig. 2. An equivalent model of photosensitive field emitters. This model is constructed the n-type Si field emitter and conventional p–n junction photodiode, which are connected in series.

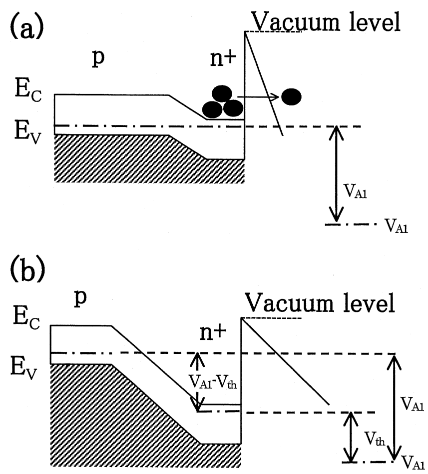

Fig. 3. A band diagram of a proposed photosensitive floating field emitter at a dark condition.

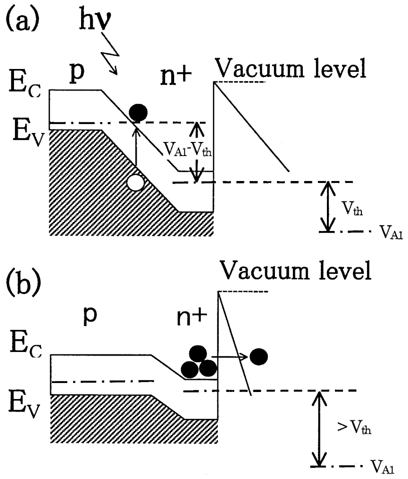

Fig. 4. A band diagram of a proposed photosensitive floating field emitter at an irradiation condition.

the anode and the floated tip also increases, and then electrons, which correspond to the light illumination, are emitted.

4. Results and discussion

4.1. Emission characteristics of non-gated type photocathode

At first, a field emitter type photocathode with non-gated type field emitters and a-Si:H photodiode film was fabricated and measured in a vacuum chamber (the base pressure was 7×10^{-9} Torr) [6]. The distance between the anode and the chip of n-type field emitter array was kept at 10 μm. The Au electrode of the photodiode film was grounded and the anode was biased to 640 V. The light was provided by LED (light emitting diode) with a centred wavelength of 680 nm.

The relation between the light intensity and the emission current for the photocathode is illustrated in Fig. 5. The solid line indicates the emission current corresponding

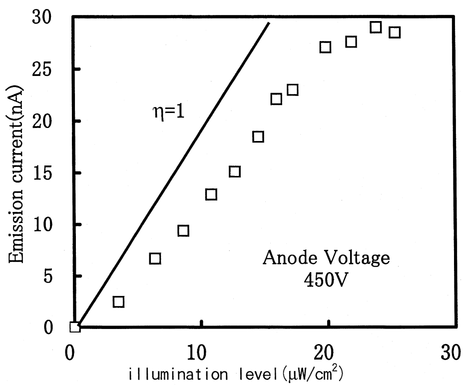

Fig. 5. The dependence of the emission current on the incident light intensity of the non-gated photosensitive device fabricated with a-Si:H p–i–n photodiode film.

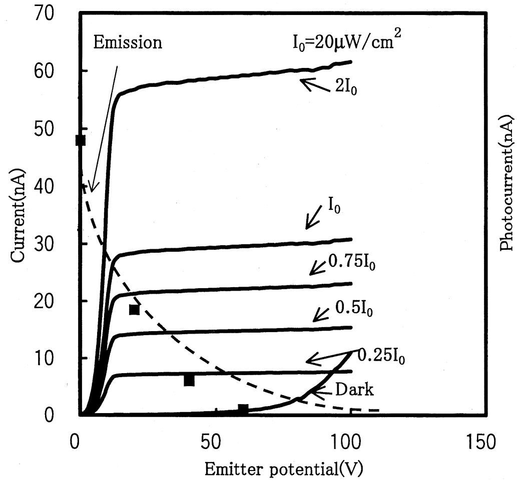

Fig. 6. The load line characteristic of the n-type silicon emitter superimposed upon the a-Si:H pin photodiode film characteristic.

to 100% quantum efficiency ($\eta = 1$). It was found that the emission current is proportional to the illumination intensity and the effective quantum efficiency is about 70%, and the emission current has a tendency to be saturated at high illumination levels. A detectable maximum illumination intensity is about 20 $\mu W/cm^2$. This saturation phenomenon of the emission current is illustrated in Fig. 6, which shows the load line characteristic of the n-type silicon emitter superimposed upon the a-Si:H pin photodiode film characteristic. At low illumination levels, the operating points exist in the saturation region of the photocurrents characteristics. However, as illumination intensity is increased, the operating points moved to a non-saturation region. In this region, the emission current are no longer proportional to the illumination intensity and have a tendency to be saturated. It seems that the saturation phenomenon is caused by a low transconductance (g_m) characteristic of the non-gated field emitter.

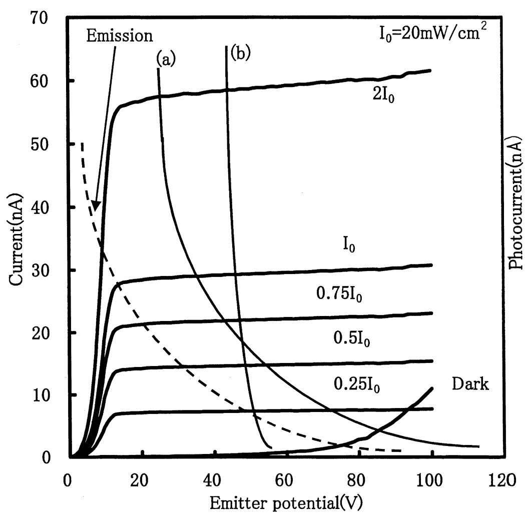

Fig. 7. Solutions to expand the dynamic rage of the photosensitive field emitter.

4.2. Solutions to expand the dynamic range

As shown in Fig. 7, there are two ways to expand the dynamic range of the photocathode. The first solution is to increase the anode operating voltage. To increase anode voltage as shown in line (a), operating points stay in the saturation region of the photodiode characteristic at a high illumination condition. However, it was found that an emission current at a dark condition is increased. The second solution is to increase a transconductance of field emitters as shown in line (b). It was found that the operating points stay in a saturation region of the photodiode and the dark current is not increased. To adopt this method, the wide dynamic range and low dark current photocathode will be realized.

4.3. Fabrication of wide dynamic range photocathode

It is well known that a gated field emitter has a high transconductance characteristic. A fabrication processes of the photocathode constructed with a gated n-type Si field emitter tip and an a-Si:H p–i–n photodiode film is described. Fig. 8 shows the processing sequence for the photocathode with gated Si field emitter. An n-type (100) oriented silicon wafer (3 Ω cm) was used as a substrate. The SiO_2 layer (400 nm) used as a mask for etching of silicon substrate was grown by dry oxidation at 1000°C. A resist for electron beam lithography (AZPN 100 3.7 cp) was coated onto the oxidized silicon substrate. Resist patterns of 4.0 μm diameter circles were realized by electron beam lithography. The resist patterns were transferred to the oxide mask by the etching of the SiO_2 layer in buffered hydrofluoric acid (BHF) (Fig. 8(a)). After stripping and cleaning the resist, the silicon was etched isotropically by a RIE system at a depth of approximately 1.5 μm (Fig. 8(b)). An oxide film 300 nm thick, which acted as the insulator between the poly-Si gate, was grown by dry oxidation at 1000°C, and then n-type poly-Si film was deposited on the whole substrate by the low pressure CVD (chemical vapor phase deposition) system (Fig. 8(c)). The poly-Si films were grown at a substrate temperature of 650°C. The thickness of the poly-Si film was 200 nm and the resistivity was 0.13 Ω cm. After the poly-Si film was formed to electrodes by RIE, a photo-resist was coated on the substrate to carry out etching back process (Fig. 8(d)). The resist coated sample was exposed to a oxygen plasma until the top of poly-Si film was bared. The bared poly-Si film was removed by the CF_4 plasma, and the SiO_2 film was naked (Fig. 8(e)). After the etching of the Si tip of emitter by a BHF solution, the photo-resist was removed (Fig. 8(f)). Hydrogenated amorphous Si (a-Si:H) photodiode film was deposited on the back of the n-type substrate (Fig. 8(g)). An image of the scanning electron microscopy (SEM) on gated field emitter with poly-Si gate is shown in Fig. 9. The diameter of the silicon gate plateau is approximately 1 μm. The distance between the edge of the emitter and the gate is approximately 400 nm. The radius of the tip is about 40 nm.

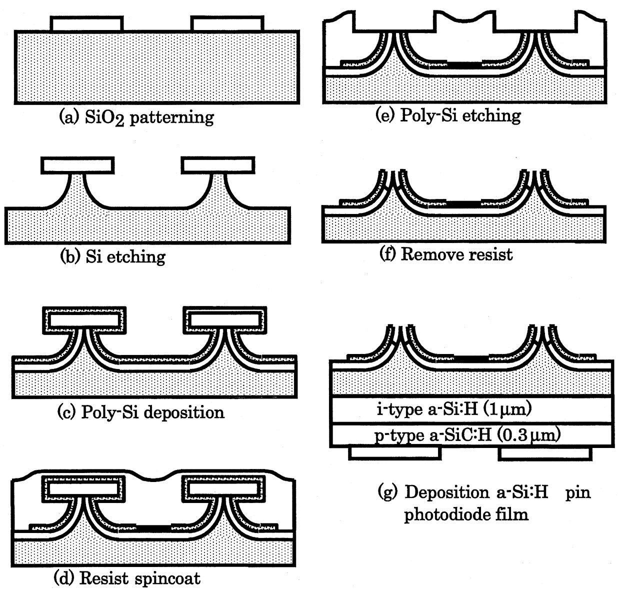

Fig. 8. A fabrication process of the gated floating field emitter.

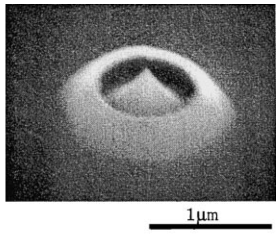

Fig. 9. A SEM photograph of the fabricated device.

4.4. Emission characteristics of the gated field emitters

Before the deposition of an a-Si:H photodiode film, the emission current characteristics of the gated Si emitters were measured. Fig. 10 shows the emission current versus the gate voltage characteristic obtained at an anode voltage of 600 V. The gate was positively biased with respect to

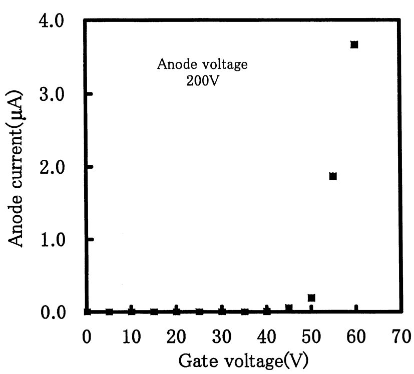

Fig. 10. The dependence of the emission current on the gate bias of the fabricated gated emitter.

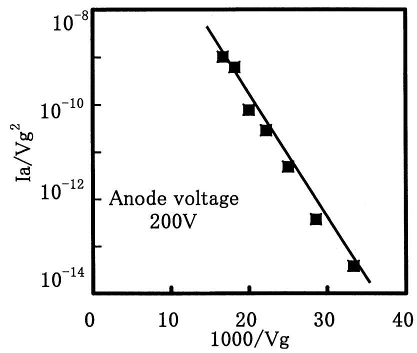

Fig. 11. The F-N plot of the emission current of the fabricated gated emitter.

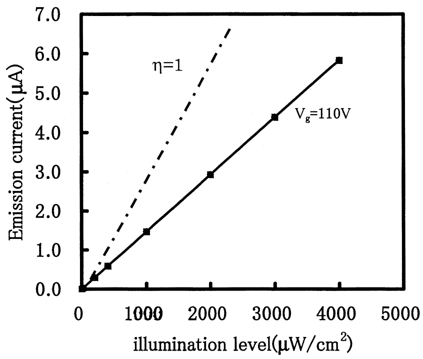

Fig. 13. The dependence of the emission currents on the incident light intensity.

the Si emitters. The anode electrode, a molybdenum rod with a diameter of 3 mm, was positioned 3 mm from the tip of the emitter. The emission current was measured under high vacuum conditions ($<1\times10^{-8}$ Torr) at room temperature. The emission current could be detected at the gate bias of 35 V. At the gate bias of 60 V, a stable current reached a value of about 3.5 μA. The transconductance of the non-gated Si field emitters was about 5×10^{-10} S. That of the gated Si emitters was about 1.4×10^{-7} S. It was found that the transconductance of the gated emitter was 280 times higher than that of non-gated emitter. From the Fowler–Nordheim (F-N) plot of the emission current, as shown in Fig. 11, the distinctive feature of the emitter is shown.

4.5. Photoelectric properties of the photocathode with the gated field emitters

Photocurrent and dark current characteristics of the a-Si:H pin photodiode film were previously measured using a TEG (Test Element Group) device. The breakdown voltage of this photodiode film was more than 150 V and the photocurrent was proportional to incident light power. The dark current is less than 0.1 nA. Typical photocurrent and dark current characteristics of the a-Si:H pin photodiode is shown in Fig. 12.

The emission characteristics of the field emitter type photocathode with gated Si emitter was investigated. Incident light intensity dependence of the emission current for the photocathode is shown in Fig. 13. The distance between the anode and the emitter array was kept at 10 mm. The Au electrode of the photodiode film is grounded. The anode and the gate of the field emitters are biased at 600 V and 110 V, respectively. The quantum efficiency was about 0.7 higher. Fig. 14 shows the load line characteristic of the gated Si field emitter superimposed upon the a-Si:H pin photodiode film characteristic. A voltage applied to the a-Si:H pin photodiode film in dark condition could be estimated to be about 75 V, which was calculated by subtracting the threshold voltage of the emitter from the anode voltage ($110-35=75$ V). The operating points of this photocathode exist in a saturation region of the photodiode. Fig. 13 shows that detectable maximum illumination intensity is about 4000 μW/cm^2 and the minimum detectable illumination intensity is 2 μW/cm^2, which corresponds to the light intensity of moonlight. It was found that its dynamic range was about 200 times wider than that of non-gated type photosensitive field emitters. The dark current of the fabricated device is less than 0.1 nA.

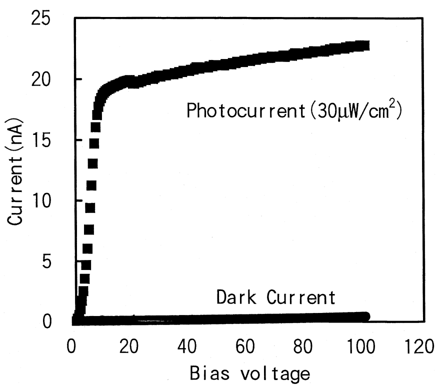

Fig. 12. Typical photocurrent and dark current characteristics of the a-Si:H pin photodiode films. Irradiated light power is 30 μW/cm^2.

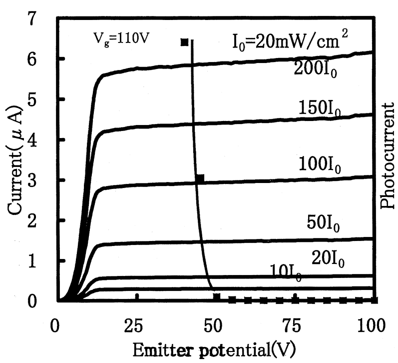

Fig. 14. The load line characteristic of the gated silicon emitter superimposed upon the a-Si:H pin photodiode film characteristic.

5. Conclusions

A novel photocathode constructed using a gated Si field emitter tip and an a-Si:H p–i–n photodiode film was proposed. The emission current from the photocathode is proportional to illumination intensity. The detectable maximum illumination intensity and the quantum efficiency, respectively was about 4000 $\mu W/cm^2$ about 0.7 higher. Its dynamic range was about 200 times wider than that of the field emitter type photocathode using non-gated field emitter.

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Biographies

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