Electron emission from porous silicon planar emitters

Hidenori Mimura,[a)] Kentaro Miyajima, and Kuniyoshi Yokoo
Research Institute of Electrical Communication, Tohoku University, Katahira, Aoba-ku, Sendai 980-8577, Japan

(Received 18 December 2002; accepted 28 April 2003; published 31 July 2003)

Porous silicon planar emitters were fabricated by depositing a thin Au film on a conventional porous Si and their emission characteristics were examined. The emission currents and energy distributions were measured for the emitters with various Au thicknesses and for cesiated ones. The experimental results suggest that the emission mechanism of the porous silicon emitter studied in this work is conventional field emission, in which electrons are emitted from nanocrystals in the porous silicon directly into a vacuum. [DOI: 10.1116/1.1584470]

I. INTRODUCTION

Many types of cold cathodes have been developed for applications to vacuum microelectronic devices including high-frequency and environment hard electronic devices, and a flat panel display. The cathodes are expected to have high current density at low extraction voltage and to be stable in operation for the aforementioned applications. Lately, the porous Si planar emitter, which is composed of an Au contact, a porous Si layer, an n^+ Si substrate, and an ohmic back contact, has been receiving much interest from the expectation to satisfy these requirements.[1–3] When a positive bias voltage around a few tens of volts is applied to the Au electrode with respect to the back contact of the substrate, electrons are uniformly emitted into a vacuum without spike noises. In addition, the emitter has some advantages, such as a narrow emission angle and insensitivity to gas pressure. A large-scale polycrystalline silicon based porous Si planar emitter also has been fabricated on a quartz glass substrate and its emission characteristics have been investigated for an application to a flat panel display. The emission current from the emitter is stable, uniform over the emitting area, and almost independent of the gas pressure.[4] The model, based on a quasi-ballistic transport in the nanometer size crystalline Si and a cascade tunneling through the potential barriers of SiO_2 formed on the nanosilicon surface, is proposed as one of the emission mechanisms of the porous Si planar emitter.[5] The details of the emission mechanism, however, are not still clear.

As the first step to understanding the emission mechanism of the porous Si planar emitter, we fabricated the emitters by a conventional anodization technique of porous Si and deposition of a thin Au film on the porous Si, and investigated their emission characteristics. The porous Si used in this work was a single layer; different from a multilayer or a graded multilayer studied previously.[2] The porous Si was not thermally oxidized to examine the emission characteristics of a bare porous Si emitter. The emission currents and energy distributions were measured for several emitters with various Au thicknesses and for cesiated ones. The experimental results suggest that the electron emission occurs from the nanocrystals in the porous Si by conventional field emission.

II. EXPERIMENTS

Porous Si was formed by electrochemical anodization of n^+-single crystalline Si (100) wafers with a resistivity less than 0.05 Ω cm. The anodization was carried out in the solution of HF (50%):ethanol=1:1 at current densities of 50–100 mA/cm^2 for 5–10 min under the illumination of a 500 W halogen lamp positioned above the substrate. The thickness of the porous Si was several tens of μm under these conditions. An atomic force microscope (AFM) image of the porous Si anodized at 100 mA/cm^2 for 10 min is shown in Fig. 1. The surface of the porous Si is composed of many particles with a diameter from several nm to several tens of nm. No significant difference was observed for the porous Si anodized at 50 mA/cm^2, but the diameter of the particle becomes slightly larger with decreasing current density of the anodization. After anodization, a semitransparent Au film (typically, the thickness was 5 nm) was deposited on the porous Si to form an extraction gate electrode of a planar emitter structure. The area of the Au film was about 12.6 mm^2. The Au film is probably discontinuous, because AFM images revealed that the similar surface morphology was kept for the Au-deposited porous Si. An ohmic electrode was formed on the back side of the Si wafer. The emitters were mounted into a high-vacuum chamber (4×10^{-8} Torr) for the measurements of the emission characteristics. A schematic setup for the emission measurement of the planar emitter is shown in Fig. 2. The extraction voltage was applied on the Au electrode of the emitter, and the diode current (I_d) and the corresponding emission current (I_e) were measured as a function of the extraction voltage. An Al anode was located 5 mm away from the cathode, and the anode voltage was 200 V. When we measured the energy distribution of emitted electrons, the Al anode was replaced with a parallel-plate electron energy analyzer.

III. RESULTS AND DISCUSSION

Figure 3 shows a typical current–voltage characteristic of the porous Si planar emitter using a porous Si anodized at 100 mA/cm^2 for 10 min. Emission current is observed at the

[a)]Electronic mail: mimura@riec.tohoku.ac.jp

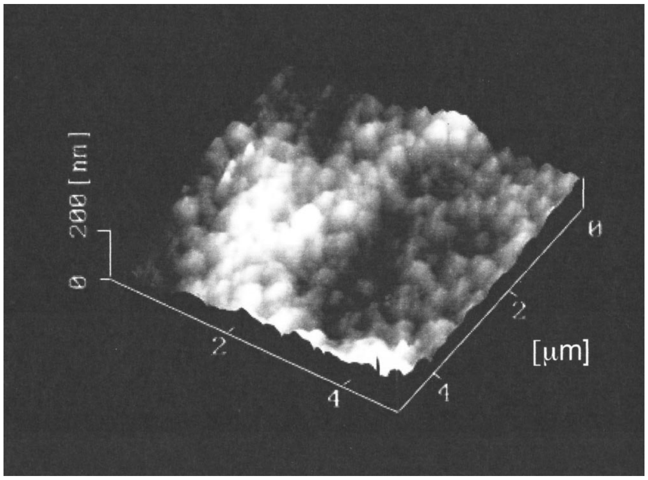

FIG. 1. AFM image of the porous Si anodized at 100 mA/cm^2 for 10 min.

voltage of 13 V. Since no rapid thermal oxidation was performed on the porous Si, the emission current is rather low as compared with the diode current.[6]

Figure 4 shows the energy distributions of electrons emitted from the porous Si planar emitter for the various voltages applied on the Au electrode. The porous Si used here was formed by the anodization at 100 mA/cm^2 for 5 min. The zero energy in the abscissa indicates the vacuum level of the Au electrode. The energy distribution is broad and strongly depends on the applied voltage. The peak and maximum energies move to higher values with increasing applied voltage.

Figures 5(a) and 5(b) show the emission characteristics and energy distributions of three emitters with various Au thicknesses, respectively. Each porous Si used here was formed at the current density of 100 mA/cm^2 for 10 min. The energy distributions were measured at the extraction voltage of 30 V. Even when we increase the Au thickness up to 40 nm, no significant reduction in the emission current is observed and high-energy electrons are still emitted from the porous Si emitter. In metal–oxide–semiconductor (MOS) tunneling cathodes, when a sufficient positive bias voltage is

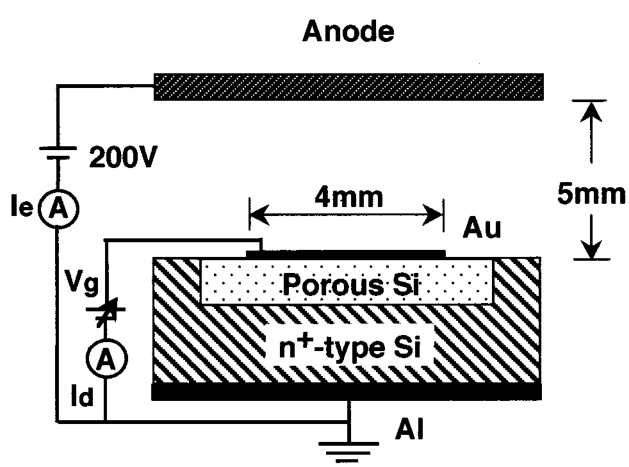

FIG. 2. Schematic experimental setup for electron emission from a porous Si planar emitter.

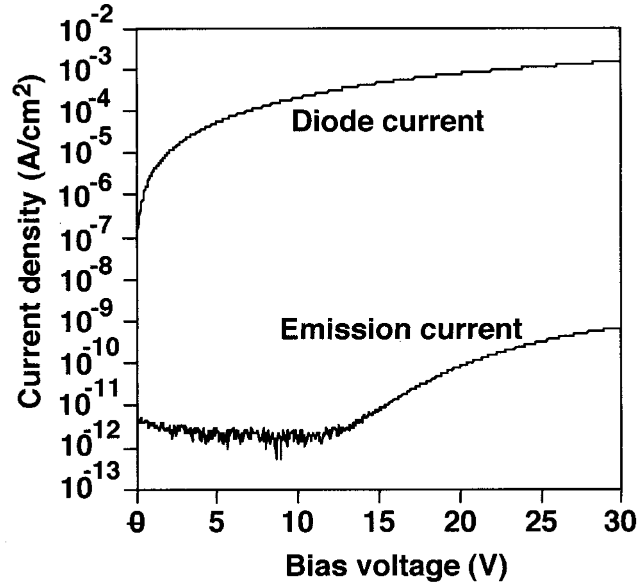

FIG. 3. Typical current–voltage characteristic of the porous Si planar emitter using a porous Si anodized at 100 mA/cm^2 for 10 min.

applied to the gate electrode with respect to the back contact of the substrate, electrons tunnel through both the SiO_2 and gate electrode of the MOS structure, and some of them with the energy larger than the work function of the gate electrode are emitted into a vacuum.[7,8] Therefore, the emission current in the MOS cathode drastically decreases with increasing the thickness of the gate electrode, due to strong electron scattering inside the gate electrode.[9] However, the porous Si emitter shows no significant reduction in the emission current, even when the Au thickness is increased. In addition,

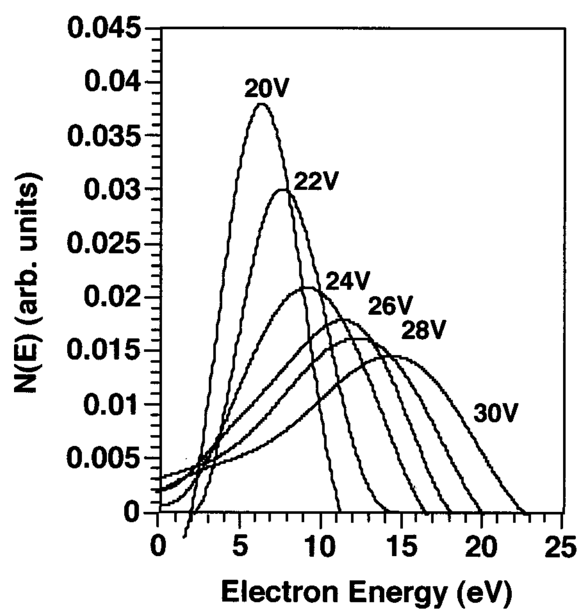

FIG. 4. Energy distributions of electrons emitted from the porous Si planar emitter for the various voltages applied on the Au electrode. The porous Si was formed by the anodization at 100 mA/cm^2 for 5 min. The zero energy in the abscissa indicates the vacuum level of the Au electrode.

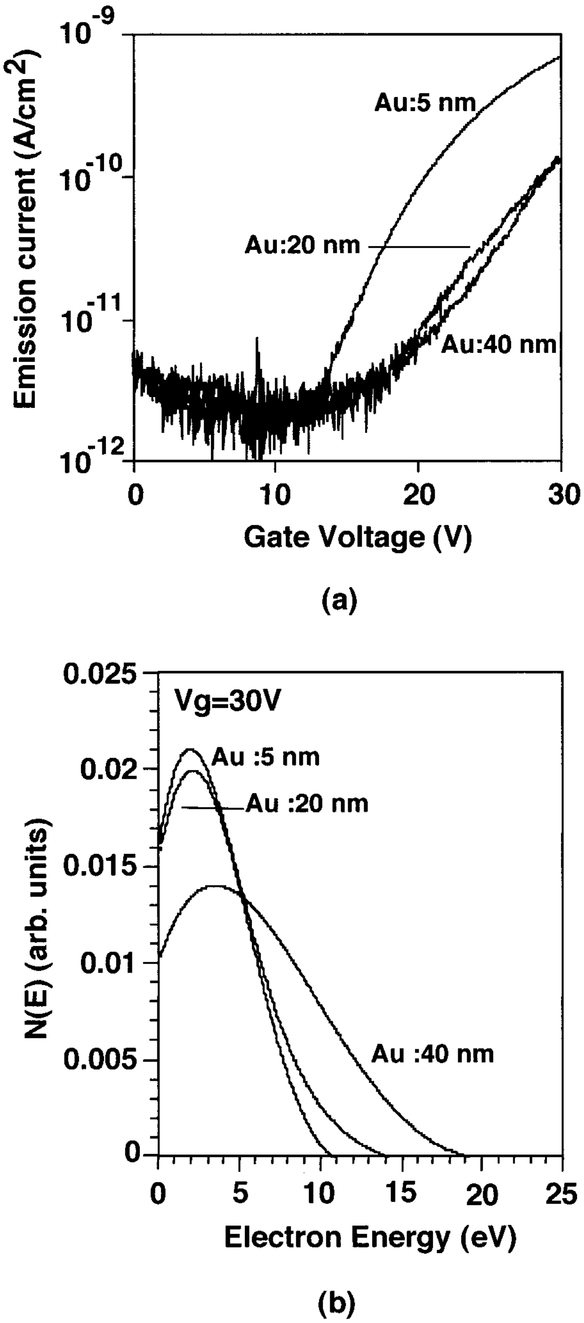

FIG. 5. Emission characteristics (a) and energy distributions (b) of three emitters with various Au thicknesses. Each porous Si was formed at the same anodization current density of 100 mA/cm^2 for 10 min. The energy distributions were measured at the extraction voltage of 30 V.

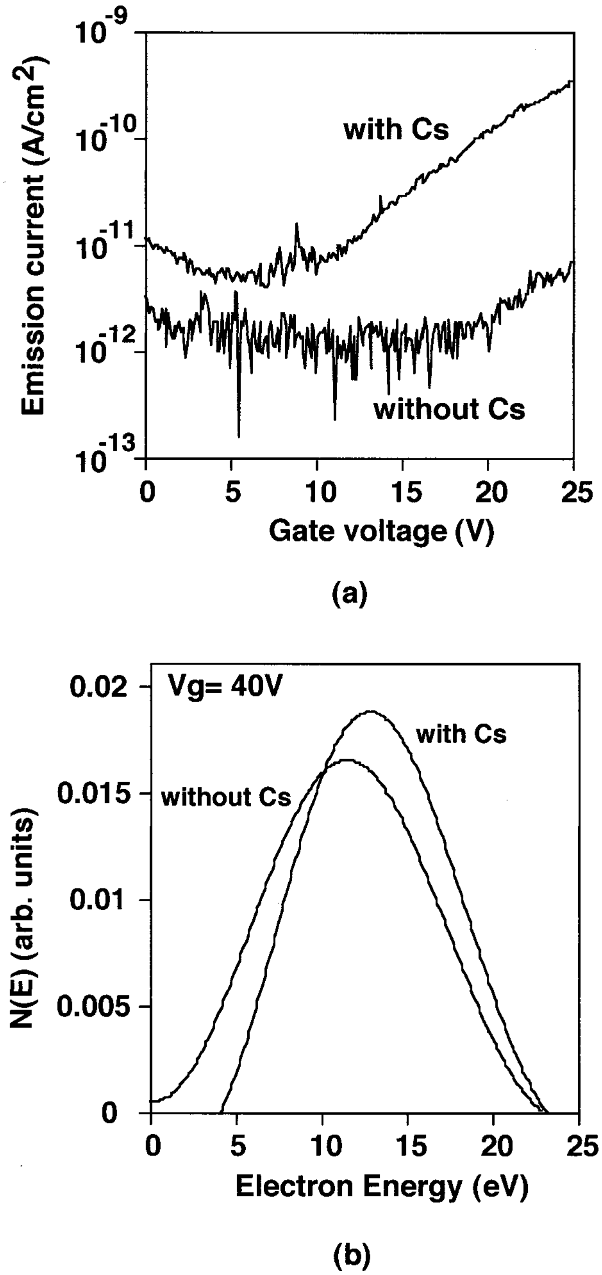

FIG. 6. Emission characteristics (a) and energy distributions (b) for the porous Si planar emitter before and after the deposition of Cs. The porous Si was formed by the anodization at 50 mA/cm^2 for 10 min. The energy distributions were measured at the extraction voltage of 40 V.

high-energy electrons should drastically decrease with increasing Au thickness due to the strong electron scattering, if electrons pass through the inside of the Au electrode. However, the high-energy electrons are still emitted from the porous Si planar emitter with the sufficiently thick electrode of 40 nm. Therefore, these results suggest that the emitted electrons do not pass through the inside of the Au electrode.

Figures 6(a) and 6(b) show the emission characteristics and energy distributions for the porous Si planar emitter before and after the deposition of Cs. The Cs was deposited on an entire surface of the porous Si planar emitter. The porous Si used here was formed by the anodization at 50 mA/cm^2 for 10 min. The energy distributions were measured at the extraction voltage of 40 V. The Cs deposition causes a considerable increase in the emission current, but no significant change in the energy distribution, as shown in Figs. 6(a) and 6(b). On the other hand, it is well known that cesiation drastically increases not only the emission current, but also low-energy electrons in the energy distribution for the MOS cathode, because the cesiation lowers the work function of the gate electrode. These experimental results suggest that electrons are directly emitted from nanocrystals in the porous Si into a vacuum by conventional field emission and not emitted from the Au electrode after passing through the inside of the Au electrode, which is contrary to the previously proposed model.[5] In addition, the structure of the porous planar emitter is similar to the triple junction proposed by Geis *et al.*[10] However, the emission mechanism is probably different from that of the triple junction, because the energy spread of the porous Si emitter is considerably broad. The porous Si emitter, which is composed of nanocrystals in the porous Si, native oxide on the surface of the porous Si and a semitransparent Au electrode, is eventually one of the field-emitter arrays integrated with a tremendously huge number of nanosize field emitters.

IV. CONCLUSIONS

We have fabricated porous Si planar emitters by depositing a thin Au film on conventional porous Si and examined their emission characteristics. The energy distribution strongly depends on the applied voltage, and the peak and maximum energies move to higher values with increasing applied extraction voltage. The increase in the thickness of the Au electrode from 5 nm up to 40 nm does not cause a significant reduction in both the emission current and the high-energy electrons. In addition, the cesiation of the emitter shows no significant change in the energy distribution. These results suggest that the emission mechanism of the porous Si emitter studied here is conventional field emission from the nanocrystals in the porous Si. Although further investigation is still necessary to completely understand the emission mechanism of the porous Si planar emitter, the planar field emitters using nanoparticles, not only porous Si but also many other semiconductor and metal particles, may be promising candidates for the fine emitter with a high current density, a low extraction voltage, and stable emission.

ACKNOWLEDGMENTS

A part of this work was carried out at the Super Clean Room of Laboratory for Electronic Intelligent System, Research Institute of Electrical Communication, Tohoku University. This work was supported in part by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science, and Technology, Japan.

[1] X. Sheng, H. Koyama, and N. Koshida, J. Vac. Sci. Technol. B **16**, 793 (1998).
[2] N. Koshida, X. Sheng, and T. Komoda, Appl. Surf. Sci. **146**, 371 (1999).
[3] X. Sheng, A. Kojima, T. Komoda, and N. Koshida, J. Vac. Sci. Technol. B **19**, 64 (2001).
[4] T. Ichihara, T. Komoda, Y. Honda, Y. Watanabe, T. Hatai, T. Baba, K. Aizawa, and N. Koshida, Proc. Int. Display Workshop (2001), p. 1193.
[5] T. Komoda, X. Sheng, and N. Koshida, J. Vac. Sci. Technol. B **17**, 1076 (1999).
[6] X. Sheng, H. Koyama, N. Koshida, S. Iwasaki, N. Negishi, T. Chuman, T. Yoshikawa, and K. Ogasawara, J. Vac. Sci. Technol. B **15**, 1661 (1997).
[7] K. Yokoo, H. Tanaka, S. Sato, J. Murota, and S. Ono, J. Vac. Sci. Technol. B **11**, 429 (1993).
[8] H. Mimura, Y. Abe, J. Ikeda, K. Tahara, Y. Neo, H. Shimawaki, and K. Yokoo, J. Vac. Sci. Technol. B **16**, 803 (1998).
[9] K. Yokoo, G. Koshita, S. Hanzawa, Y. Abe, and Y. Neo, J. Vac. Sci. Technol. B **14**, 2096 (1996).
[10] M. W. Geis, N. N. Efremow, K. E. Krohn, J. C. Twichell, T. M. Lyszczarz, R. Kalish, J. A. Greer, and M. D. Tabat, Nature (London) **393**, 431 (1998).