Development of Low-Voltage-Driven Propellantless Cathodes with High-Current Density Based on Graphene-Oxide-Semiconductor Structure

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Abstract: Graphene-oxide-semiconductor (GOS) planar-type electron sources can be driven by applying 10–20 V with high emission current density of 10–100 mA/cm^2. We have proposed low-voltage-driven propellantless cathodes for miniature ion thrusters using the GOS planar-type electron sources. We have fabricated the electron sources with a single emission area of 50 μm × 50 μm or 100 μm × 100 μm, and successfully achieved the emission current density of over 100 mA/cm^2. Moreover, we accomplished the emission current of 2.1 mA using the electron sources with hundreds of 100 μm × 100 μm emission area.

Nomenclature

I	=	emission current
J	=	emission current density
S	=	emission area
η	=	emission efficiency

I.Introduction

OVER the last decade, the global market of the deep space mission or broadband constellations with small-spacecraft have rapidly increased.[1] To execute these space missions, miniature propulsion systems are mounted on small-spacecraft and generate the thrust to the spacecraft in deep space or around the earth. In recent research about small-spacecraft, an ion thruster has been utilized as a propulsion system because of its high specific impulse and delta-v.[2-4] To prevent extracted ions from flowing backward to the plasma sources, electrons are emitted to the ion

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beams from neutralizers. [5-7] However, neutralizers do not contribute to the thrust. Therefore, it is desirable to reduce the propellant and power consumption of neutralizers on small-spacecraft as much as possible.

As pioneering propellantless neutralizers of ion thrusters or electron emitters of space tether, field emission cathodes (FECs) have been proposed.[8-10] FECs can emit electrons about 10 mA just by applying an electric field to the materials on the metal. However, FECs need to apply a high voltage of over 100 V to extract electrons from the surface of the materials. Furthermore, the emission current density to the surface area is under 0.2 mA/cm^2. Hence, to obtain the emission current of several mA using conventional FECs, the cathode size becomes approximately 10 cm × 10 cm as large as 1U CubeSat. In order to realize the propellantless cathodes for small-spacecraft, FECs must lower the drive voltage and increase the emission current density.

Therefore, we have proposed graphene-oxide-semiconductor (GOS) planar-type electron sources as propellantless cathodes for space propulsion of small-spacecraft.[11] The GOS type electron sources can be driven by applying only 10–15 V with much higher emission current density of 10–100 mA/cm^2 than that of the other conventional FECs.[12-14] As shown in Fig. 1, the GOS type electron sources consist of four layers; an n-type Si substrate, thin SiO_2 as an insulating layer, graphene as an upper layer, and Ni and Ti as a contact layer to the graphene. By applying the gate bias between the n-type Si and the contact layer, the width of the potential barrier decreases, and then electrons accumulated in the Si substrate pass through the insulating layer by tunneling effect. Transmission electrons which have energy exceeding the work function of graphene are emitted into a vacuum through the graphene layer. Here, the ratio of the emission electrons from the graphene layer to the electrons passed through the insulating layer is defined as emission efficiency. The GOS type electron sources achieved the emission efficiency of 10–30%, which is exceedingly higher than that of other electron sources based on metal-oxide-semiconductor structure on the order of 0.01% or less.[15] However, the emission current of the GOS type electron sources is still lower than 10 μA. It is necessary to expand the emission area of the GOS type electron sources and achieve the emission current of several mA as much as conventional FECs.

To fabricate GOS type electron sources with larger emission areas, there are two approaches: deploying a single several mm^2 emission site or high-density small emission sites in a several mm^2 wafer. To fabricate a single large emission site, it is necessary to fabricate it without defects in the insulating layer because the defects cause the leakage current and make it difficult to emit electrons from the whole emission area. On the other hand, if the emission area is divided into small emission sites, the unfavorable effect by the defects is inhibited in the small emission site. Therefore, we tried to develop the propellantless cathode using the GOS type electron sources with hundreds of small emission sites.

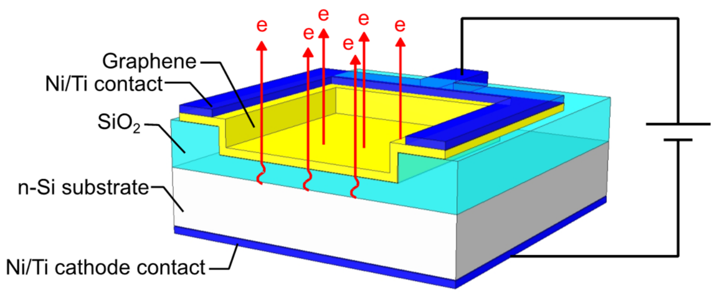

Figure 1. A schematic of Graphene-oxide-semiconductor (GOS) planar-type electron sources.

II. Experimental Procedure

A. Fabricating Process

Figure 2 shows the main three fabrication procedures of the GOS type electron sources.

a) The pattern of emission areas is fabricated by etching the 300 nm SiO_2 layer on the Si substrate. Then, the thin SiO_2 layer is grown by 900°C thermal oxidation.
b) Using the chemical vapor deposition (CVD), 2.5 nm graphene is directly synthesized on the thin SiO_2 layer.
c) After a part of graphene is etched by the photolithography process, Ni and Ti are deposited as contact electrodes on both the top and bottom of the wafer by electron beam vacuum evaporation technique.

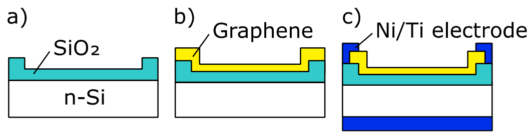

Figure 2. Fabrication process of Graphene-oxide-semiconductor planar-type electron sources. a) Growth of thin SiO_2 on the Si substrate by thermal oxidation. b) Synthesizing the graphene layer on thin SiO_2 layer by CVD. c) Deposition of Ni and Ti as a contact electrode by electron beam vacuum evaporation.

To fabricate many emission sites with high quality insulating layer, the temperature in graphene synthesis process should be lowered to avoid defects in the insulating layer. Hence, we applied plasma-enhanced CVD (PECVD) by which the graphene can be synthesized at lower temperature than thermal CVD.

B. Measurement of *I-V* characteristics

Figure 3 shows a schematic diagram of the experimental setup. The chamber vacuum pressure at the experiment is 1.0 × 10^{-6} Pa. Applying the gate bias V_G in the range of 0–20 V at 0.1 V step, electrons are emitted and encountered the collector SUS plate biased at 1 kV to avoid space-charge limitation. We measured the electron emission current I_E in the collector and the total current I_T in the Si substrate.

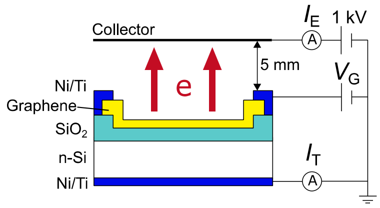

Figure 3. Circuit diagram of the experimental setup of *I-V* characteristics.

C. Selection of emission area

Firstly, to decide the single emission site which can emit electrons with high emission current density and emission efficiency, we fabricated the GOS type electron sources with different single emission sites (50 µm × 50 µm, 100 µm × 100 µm, 200 µm × 200 µm, and 500 µm × 500 µm) and measured the emission characteristics. The characteristics are evaluated from the emission current density J shown in Eq. (1),

$$J = I/S, \tag{1}$$

where I is the emission current and S is the emission area, and the emission efficiency η shown in Eq. (2),

$$\eta = I_E/I_T. \tag{2}$$

Next, we estimated that hundreds of small emission sites are needed to achieve the emission current of several mA because the emission current from 50 µm × 50 µm area is several µA. Hence, we fabricated the electron sources with hundreds of small emission sites in 3 mm × 3 mm area.

III. Results and Discussion

A. Emission performance of a single emission site

Figure 4 shows *J-V* characteristics of the GOS type electron sources with a single emission site of 50 µm × 50 µm and 100 µm × 100 µm. The electron source with a single 50 µm × 50 µm emission site maintained the emission efficiency of over 20% in the range of 8.0–11.5 V and achieve the maximum emission current density of 230 mA/cm^2 at 14.1 V. On the other hand, the electron source with a single 100 µm × 100 µm emission site maintained over 20% in 7.5–14.0 V and achieve 184 mA/cm^2 at 14.0 V. However, the emission current of both electron sources dropped in the range of 14.2–15.0 V. We consider that the breakdown of the insulating layer occurred at the gate bias and the leakage current partially increased. Concerning the electron sources with 200 µm × 200 µm or 500 µm × 500 µm site, they were not driven with high emission current density due to leakage current. We assume that the defects in the insulating layer are likely to be formed in larger emission site than 100 µm × 100 µm and cause the leakage current.

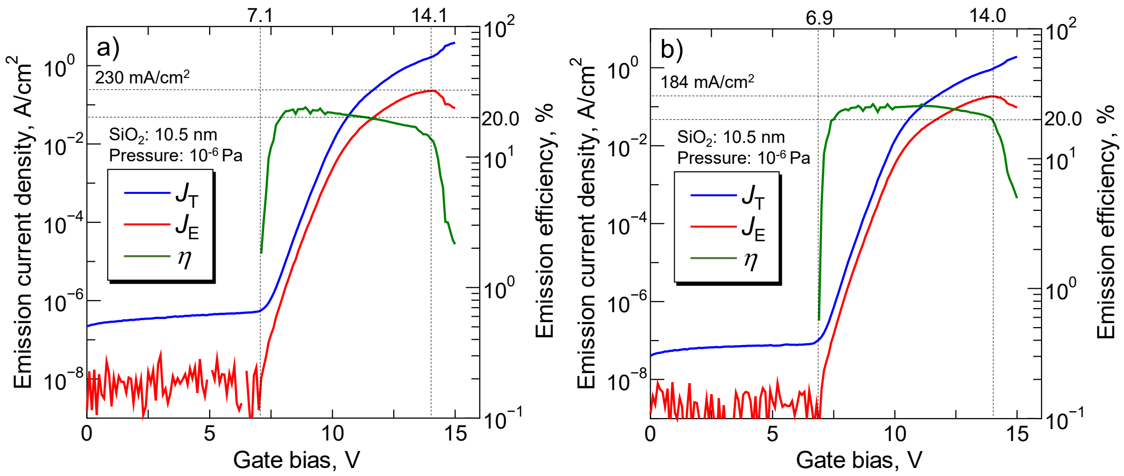

Figure 4. *J-V* characteristics of the GOS type electron sources with a single emission site. a) 50 µm × 50 µm emission site. b) 100 µm × 100 µm emission site.

Altogether, we achieved high emission current density of over 100 mA/cm^2, and we apply 50 µm × 50 µm or 100 µm × 100 µm site as small emission sites.

B. Emission performance of the electron sources with high-density small emission sites

The single emission site should be as large as possible to deploy the high-density small emission sites in a wafer. In our deployment concept of small emission sites, the total emission area per wafer with massive 100 µm × 100 µm sites are approximately twice higher than that with massive 50 µm × 50 µm sites. Therefore, we fabricated the GOS type electron sources with hundreds of small emission sites of 100 µm × 100 µm in a several mm^2 wafer. Figure 5 shows *I-V* characteristics of the GOS type electron sources which have 380 emission sites of 100 µm × 100 µm in a 3 mm × 3 mm wafer. At the gate bias of 13.4 V, the maximum emission current of 2.1 mA was obtained successfully. The emission current density to the total emission area of 3.8 mm^2 at 13.4 V is 55.3 mA/cm^2, which is lower than that of the electron source with a single 100 µm × 100 µm emission site in the previous section. Hence, we assume that the electrons are not emitted from all the small emission sites. Although, the emission current density to the wafer size of 3 mm × 3 mm at 13.4 V is 23.3 mA/cm^2, which far surpass that of other conventional FECs. After achieving the maximum emission current, the emission current of the electron sources dropped at the almost same gate bias of the electron source with a single emission site. In other words, the electron sources which have 10.5 nm insulating layer can be driven up to the breakdown voltage of about 13 V. In conclusion, we succeeded to fabricate the low-voltage-driven propellantless electron sources which can be driven with high emission current density.

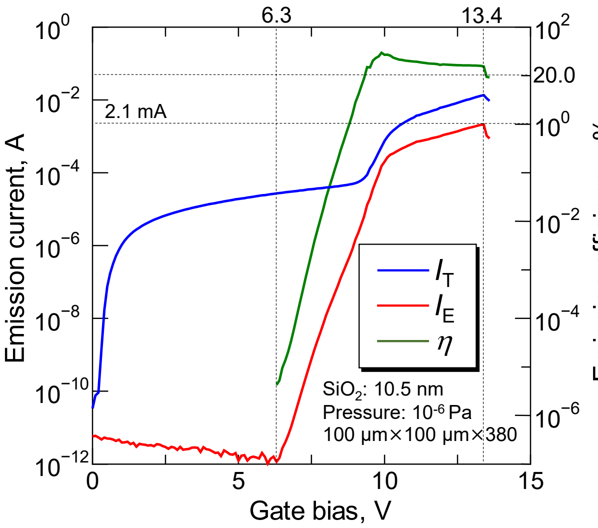

Figure 5. *I-V* characteristics of the GOS type electron sources with 380 emission sites of 100 µm × 100 µm in a 3 mm × 3 mm wafer.

IV. Conclusion

We have proposed Graphene-oxide-semiconductor (GOS) planar-type electron sources as promising propellantless low-voltage-driven neutralizers for miniature ion thrusters. To obtain the emission current of several mA, we fabricated the electron sources with hundreds of small emission sites and measured *I-V* characteristics in a vacuum. As a result, we achieved the emission current of 2.1 mA (corresponding to the emission current density of 23.3 mA/cm^2 to the wafer size) at the gate bias of 13.4 V by using the electron source with 380 emission sites of 100 µm × 100 µm in a 3 mm × 3 mm wafer. We have succeeded in achieving the emission performance of the GOS type electron sources, which can be used as neutralizers of miniature ion thrusters.

Acknowledgments

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