Stability of cross-shaped electron beam in a vacuum magnetic sensor with a p-Si field emitter tip

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Abstract

The stability of the cross-shaped electron beam (EB) in a vacuum magnetic sensor with a vertical p-type Si field emitter tip was investigated. The magnetic flux parallel to the EB, B_z , was detected by rotational displacements $\Delta\Phi$ of the cross-shaped EB between the anodes, and sensed as a differential anode current normalized by total current $\Delta I_a/I_a$. The fluctuation in $\Delta\Phi$ was within 1% over a duration of 90 s at $B_z = 3.0$ mT. The magnetic flux normal to the EB, B_x , was detected by the translational displacement ΔL_y of the cross-shaped EB along the y direction, and sensed as $\Delta I_a/I_a$. The fluctuation in ΔL_y was also within 1% at $B_x = 3.0$ mT. These results demonstrate that this sensor with a vertical p-Si emitter tip using the cross-shaped EB is able to detect the magnetic flux in an arbitrary direction with high sensitivity and stability.

Keywords vacuum microelectronics, field emitter, vacuum magnetic sensor, focusing electron beam, current stability

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1 Introduction

Recently, vacuum microelectronics devices exploiting ballistic electrons in vacuum have attracted attention since the realization of the micrometer-sized field emission cathode by Spindt and colleagues.^{1,2)} Vacuum microelectronics devices are called field emitters because the emitters, formed by fine processing technology, generate an emission field of electrons. Much work have been devoted to metal electrodes as field emitters.^{3–6)} Such devices have been studied in a wide range of applications such as displays,^{2,7,8)} microwave waveguides,^{9,10)} free electron lasers,¹¹⁾ electron microscopes,^{12,13)} vacuum gages, photo sensors,^{14–18)} and reliable uniform and high current emissions.^{19,20)}

The present study focuses on magnetic sensors using features of vacuum microelectronics devices, particularly those with separate electrodes.²¹⁾ At first, magnetic sensors, wherein the transport of carriers in the semiconductor is exploited, were studied to meet size-reduction requirements.^{22–24)} However, these devices presented difficulties regarding performance improvements such as enhancing sensitivity. Such difficulties were mostly caused by the limited mobility of carriers in the semiconductors. For this reason, the research focus gradually shifted to magnetic sensors using the transport of electrons in vacuum. Vacuum magnetic sensors (VMS) having a horizontal field emitter array (FEA) made of tungsten (W)^{25–27)} demonstrated their superiority over semiconductor-based magnetic sensors in regard to robustness and sensitivity.²⁸⁾ The characteristics showed a sensitivity as high as 1,000%/T (T being the unit of magnetic flux density B). This sensitivity is about one order of magnitude higher than that of semiconductor-based sensors. However, such VMSs are sensitive only to B fields normal to the FEA. We therefore proposed a distinctive three-dimensional (3D) VMS concept and fabricated vertical emitter tips that generate a cross-shaped electron beam (EB) for the 3D-VMS.²⁹⁾

Scanning electron microscopy (SEM) image and the cross sectional schematic of the proposed VMS are shown in Figs. 1(a) and (b), respectively. The VMS using a vertical emitter consists of a single cone-type Si emitter tip in the center, a cross-shaped gate electrode, four in-plane focusing lens electrodes, and anode plates as shown in Fig. 1(c). The anode is divided into eight parts in a radial pattern and positively biased to collect electrons. The feature of our VMS is the cross-shaped EB produced by the cross-shaped electrode in Fig. 1(a). EB emitted from the emitter tip experiences the electric field caused by the focusing lens electrodes, and forms cross-shaped EB patterns as schematically shown in Fig. 1(d). By using such

cross-shaped EB and separated anodes, the proposed VMS can detect magnetic flux in an arbitrary direction. Briefly, when the magnetic flux is parallel to the EB (B_z), the EB rotates around the z axis, leading to the difference in anode current ($\Delta I_a/I_a$) between two neighboring anode electrodes because of the cross-shaped EB. Here, ΔI_a is the imbalance between the two anode parts we choose, and I_a is the total anode current detected by them. By detecting this difference, we can detect B_z . The rotation of EB is caused by the Lorentz force acting on the emitted electrons from the tip because they also have velocity components normal to the tip-anode direction.³⁰⁾ When the magnetic flux is normal to EB, the translational displacement of the cross-shaped EB occurs, inducing $\Delta I_a/I_a$. In any case, we can choose two anode electrodes out of the eight ones, and measure $\Delta I_a/I_a$. Currents due to the field emission of electrons fluctuate in principle because they are based on a quantum effect. However such fluctuations mitigate in the proposed VMS by detecting the imbalance ΔI_a normalized by the total anode current I_a to suppress the effect of the noise in field emission. The VMS is thus robust against common mode noise.³¹⁾ We achieved good linearity in detecting currents with the VMS subject to an external field B , with a sensitivity of 10,000 %/T for this structure.^{31–34)} However, we have yet to investigate the current stability of the VMS using Si field emitter tips. In this work, we measured the current stability of p-type Si VMS over a duration of 90 s when the magnetic flux is parallel to the EB (B_z) and normal to the EB (B_x).

2 Experimental methods

The field emitter tips were fabricated by a conventional Spindt-type production technique³⁵⁾ using a p-type Si substrate with a resistivity ρ of approximately 30–50 Ωcm . The fabrication process flow including SEM images is shown in Fig. 2. Briefly, a 0.3- μm -thick SiO_2 layer was first made by thermal oxidization, and a 1- μm -thick positive photoresist was spin-coated and a 1.5- μm -diameter disk pattern was made using the photolithography technique on the Si substrate. The resist pattern was transferred to the SiO_2 layer by wet etching with buffered hydrofluoric acid (BHF); the resist was removed afterwards. Reactive ion etching (RIE) was performed with SF_6 gas to shape the tip into a cone underneath the SiO_2 disk pattern. The surface of the Si substrate was again thermally oxidized to sharpen the emitter tip. Then a 0.2- μm -thick Nb layer was deposited by EB evaporation for the gate plate. The SiO_2 disk pattern was lifted off by wet etching with BHF to complete the emitter tips. After this process, the surface of the Si emitters was terminated by H atoms as described in Ref. 32. Finally, the

Nb layer was patterned by RIE to form electrodes for gate and focusing lens in the same plane on the substrate.³²⁾

The SiO₂ layer underneath the gate electrode (Fig. 2) is approximately 1 μm thick. The diameter of the gate opening is about 2 μm . The cross-shaped gate is 2 μm wide and 0.9 mm long. Each focusing lens electrode is separated from the gate electrode by 2 μm . Similar emitter tips using an n-type Si substrate with $\rho = 1\text{--}2\ \Omega\text{cm}$ were formed for comparison. The device was set in a vacuum chamber with a pressure below $1.33 \times 10^{-6}\ \text{Pa}$ and was connected to a power supply and some measurement equipment. The anode plate was biased to 700 V and the emission current $I_a (= I_{a1} + I_{a2})$, and the anode-current imbalance $\Delta I_a = |I_{a1} - I_{a2}|$ were measured.

3 Results and discussion

3.1 Operation principle of Si field emitter

We herein explain the operation principle of the n-type and p-type Si emitter tips (Figs. 3 and 4). The distance between the anode plate coated with ZnO:Zn phosphors and the emitter tip (d) is about 5 mm, and is used for beam profile monitoring. The emitter is grounded through a 0.11 M Ω resistor R , and the gate and focusing lens electrodes are grounded through a voltage source at voltages V_g and V_f , respectively. The electron field emissions occur by applying V_g to the gate electrode around the emitter. The emitted electrons are accelerated toward the anode electrodes along the z direction by V_a . We next describe how the electrons are supplied to the Si emitter tips. Figure 4 shows schematic diagrams of the energy band for (a) n-Si/SiO₂ and (b) p-Si/SiO₂ regions under the gate electrode. For an n-type Si emitter tip, electrons are majority carriers. A large value of V_g induces an accumulation of electrons at the n-Si/SiO₂ interface, and they are supplied to the n-Si emitter, resulting in an electron field emission because of a strong electric field around the emitter tip. In contrast, electrons are minority carriers in the p-type Si emitter tip. The large value of V_g induces an inversion region at the p-Si/SiO₂ interface. Electrons thermally excited from the valence band to the conduction band accumulate there, and are supplied to the p-Si emitter, giving rise to an electron field emission. In both cases, the area of cross-shaped gate electrodes is sufficiently large to supply electrons to the emitter tip.

Figure 5(a) shows the EB profile obtained on the anode at $V_g = 65\ \text{V}$ and $V_f = 20\ \text{V}$. By decreasing V_f from 20 to 12 V while holding V_g unchanged, the EB converges into a

cross-shaped structure [Fig. 5(b)]. The observed EB profile was in agreement with the simulation result obtained using a program (SIMION-3D).³⁶⁾ As described later, the VMS is actually used in this converged configuration to detect the magnetic flux.

Figure 6(a) and (b) shows the I_a - V_g characteristics of the fabricated n-type Si and the p-type emitter tips, respectively. In the measurement, the gate and in-plane focusing lens electrodes were biased to the same voltage and varied from 0 to 60 V. The emission current appears at around $V_g = 40$ and 60 V, respectively, and increases nonlinearly with V_g . The tunneling current I_{FN} generated by the Fowler–Nordheim (FN) mechanism is given by³⁷⁾

$$I_{FN} = C_1 V^2 \exp(-C_2 / V). \quad (1)$$

Here, C_1 and C_2 are constants, and V is the applied bias voltage, corresponding to V_g in this work. Indicated by open circles in Fig. 6, the $\log(I_a/V_g^2)$ versus $1000/V_g$ plot is linear, meaning that the field emission is governed by the FN mechanism. The stability of the emitted current was measured first without focusing. For the n-type Si emitter tip, V_g and V_f were set to the same value of 45 V. With a further increase in V_g , insulation breakdown between the emitter and gate electrodes sometimes happens. The measurement result is shown in Fig. 7(a). The anode current I_a fluctuates by approximately 63 nA. Considering that the mean value of I_a was approximately 180 nA, the fluctuation in I_a (γ) was found to be approximately $\gamma = \pm \frac{63}{2}(\text{nA}) \div 180(\text{nA}) \approx \pm 18\%$. We next formed the cross-shaped EB by setting the V_f at 12 V; the result is shown in Fig. 7(b). The mean value of I_a was approximately 110 nA, and I_a fluctuates up to approximately 110 nA, corresponding to $\gamma \approx \pm 50\%$. Figure 7(c) shows the time evolution in snap shots of the EB profile on the phosphor. The EB intensity was found to fluctuate as evident in Fig. 7(b). Next, we investigated the EB stability of p-type Si emitter tips. Both V_g and V_f were set to 65 V so that the measured I_a became almost the same as that in the n-Si emitter tip. The fluctuation in the emitted current was approximately 27 nA, significantly decreasing to $\gamma \approx \pm 10\%$ in Fig. 8(a). Next, the stability of the emitted current was measured when the EB was cross-shaped at $V_g = 65$ V and $V_f = 10$ V. From Fig. 8(b), the fluctuation in I_a was further reduced to 9 nA, leading to $\gamma \approx \pm 5\%$. A constant current source, such as a field effect transistor, to the tips in series is an effective means to reduce these instabilities.³⁸⁾

Many studies have been carried out on current instability in an n-type Si emitter tip.^{39–41)} Hence, in this work, we do not go into this issue but rather focus on the current stability of a

p-type Si VMS when a magnetic flux is applied.

3.2 Stability of VMS using a p-type Si emitter tip

Stability of the VMS using a p-type Si emitter tip was investigated at $V_g = 65$ V and $V_f = 10$ V. We first studied the stability against B_z . Figure 9(a) shows images of the cross-shaped EB spot rotated by the magnetic flux B_z along the z direction. The cross-shaped EB rotates in a counterclockwise direction in a manner exactly defined by the Lorentz force interaction. The rotation angle $\Delta\Phi$ was measured [Fig. 9(b)]. The solid line shows the calculation result using SIMION-3D.³⁶⁾ Displacement $\Delta\Phi$ increases linearly with B_z , and the increase rate is approximately 7 deg/mT, leading to the differential anode current $\Delta I_a/I_a$. Figure 9(c) shows the dependence of $\Delta I_a/I_a$ on B_z . This result means that the rotational displacement can be detected with a sensitivity of approximately 1%/mT. We next investigated the stability of $\Delta\Phi$ at a fixed value of B_z . Figure 9(d) shows images of the cross-shaped EB spot at $B_z = 3.0$ mT. As presented in Fig. 9(e), the value of $\Delta\Phi$ is fairly stable, and the fluctuation is within 1%. The value of $\Delta\Phi$ decreases linearly with increasing V_a in Fig. 9(f) in accordance with calculations (solid lines). The increase in V_a decreases the transit time for electrons travelling from the emitter tip to the anode, and thus the duration for the Lorentz force to act on the electrons is shortened, resulting in a decrease in $\Delta\Phi$. Regarding the dynamic range of detectable B_z , the measured difference in anode current ($\Delta I_a/I_a$) changes periodically against B_z on the basis of the working principle of the VMS, making us difficult to determine the value of B_z . In such a case, we can detect higher B_z by setting V_a to be a smaller value to suppress the velocity of electrons along the z direction (v_z) as presented in Fig. 9(f).

Figure 10 shows the time evolution of $\Delta\Phi$ obtained for VMS using an n-type Si emitter tip at $B_z = 3.0$ mT, $V_g = 45$ V, $V_f = 12$ V, and $V_a = 700$ V. Compared to $\Delta\Phi$ being fairly stable for p-type Si VSM as shown in Fig. 9(e), the fluctuation in $\Delta\Phi$ reaches approximately 5% for n-type Si VMS. This value is much higher than that for the p-type Si VMS shown in Fig. 9(e) as anticipated from Fig. 7(b).

We next examined the stability against B_x . The B_x gives rise to the translational displacement of the cross-shaped EB in the y direction (ΔL_y) by the Lorentz force (F_y) acting on the EB ($F_y = -e v_z \times B_x$) and thereby induces $\Delta I_a/I_a$. The transit time t_0 necessary for emitted electrons to reach the anode is given by,

$$t_0 = d \sqrt{\frac{2m_0}{eV_a}}. \quad (2)$$

Therefore, ΔL_y is presented by,

$$\Delta L_y = \left| \int_0^{t_0} v_y dt \right| = \sqrt{\frac{8e}{9m_0V_a}} d^2 B_x. \quad (3)$$

Here, e is the elemental charge, m_0 is the electron rest mass in vacuum. Figure 11(a) shows images of the EB spot when increasing B_x . The measured ΔL_y from the initial position was plotted [Fig. 11(b)] together with the calculated results marked by a solid line. ΔL_y increases linearly with B_x , resulting in an increase in $\Delta I_a/I_a$ [Fig. 11(c)]. The characteristics shows good linearity and a sensitivity as high as 10%/mT. Figure 11(d) shows the time evolution of ΔL_y at $B_x = 3.0$ mT over a 90 s duration, demonstrating that ΔL_y is quite stable. On the basis of these results, we can state that the three-axis components of an external B applied in an arbitrary direction is detectable with high sensitivity and stability using a cross-shaped EB from the p-type Si emitter tip.

4 Conclusion

The Si field emitter tips were fabricated using a conventional fabrication process under photolithography and RIE, and their emission current stability was investigated in vacuum. The field emission of the current was well explained by the FN mechanism for both p- and n-type Si emitter tips. The p-Si emitter tip was much more stable than the n-type Si emitter tip. In the p-Si emitter tip, the magnetic flux parallel to the EB, B_z , was detected by the rotational displacement of the cross-shaped EB, and sensed as a differential anode current $\Delta I_a/I_a$. The sensitivity reached approximately 1%/mT. The value of $\Delta\Phi$ was fairly sensitive to B_z and stable. The fluctuation in $\Delta\Phi$ was within 1% at $B_z = 3.0$ mT. The magnetic flux normal to the EB, B_x , was detected by the translational displacement ΔL_y and sensed as $\Delta I_a/I_a$ with greater sensitivity as high as 10%/mT. The fluctuation in ΔL_y was also within 1% at $B_z = 3.0$ mT. These results demonstrate that the VMS with a vertical p-Si emitter tip exploiting a cross-shaped EB is able to detect an arbitrarily directed magnetic flux with high sensitivity.

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Fig. 1 (a) SEM image, and schematics of the (b) emitter, (c) anode electrodes, and (d) whole device structure.

Fig. 2 Fabrication process flow of VMS.

Fig. 3 Schematic of measurement system. V_g , V_f , and V_a are voltages applied to gate, focusing lenses, and anode electrodes with respect to the ground. I_e , I_g , I_f , I_{a1} , I_{a2} are currents. R is the resistance.

Fig. 4 Schematic band diagrams of (a) n-Si/SiO₂ and (b) p-Si/SiO₂ interfaces under the gate electrode along the z direction under bias voltages.

Fig. 5 EB profiles on the phosphor-covered anode obtained at (a) $V_f = 20$ V and (b) $V_f = 12$ V when $V_g = 50$ V and $V_a = 700$ V. Simulation result is also shown in (b).

Fig. 6 Emission current I_a versus gate voltage V_g characteristics for (a) n-type and (b) p-type Si emitter tips under the condition $V_g = V_f$.

Fig. 7 Emission current stability of the n-Si emitter tip under (a) non-convergent condition at $V_g = V_f = 45$ V, (b) convergent condition at $V_g = 45$ V, $V_f = 12$ V when $V_a = 700$ V. (c) Time evolution of the EB pattern on the phosphor-covered anode screen in condition (b).

Fig. 8 Emission current stability of the p-Si emitter tip under (a) non-convergent condition at $V_g = V_f = 65$ V, (b) convergent condition at $V_g = 65$ V, $V_f = 10$ V when $V_a = 700$ V.

Fig. 9 (a) Cross-shaped EB profiles at different values of B_z at $V_g = 65$ V, $V_f = 10$ V, and $V_a = 700$ V. Dependences of (b) rotational angle $\Delta\Phi$ and (c) differential anode current $\Delta I_a/I_a$ on B_z under the same condition in (a).²⁸⁾ Time evolutions of (d) EB profiles on the phosphor screen and (e) $\Delta\Phi$ at $B_z = 3.0$ mT under the same condition in (a). (f) Relationship between $\Delta\Phi$ and anode bias voltage V_a at $B_z = 2.0$ mT when $V_g = 65$ V and $V_f = 10$ V.

Fig. 10 Time evolution of $\Delta\Phi$ obtained for VMS using an n-type Si emitter tip at $B_z = 3.0$ mT, $V_g = 45$ V, $V_f = 12$ V, and $V_a = 700$ V.

Fig. 11 (a) Dependence of the translational displacement of the EB spot ΔL_y along the y direction for various values of B_x . Dependences of (b) ΔL_y and (c) $\Delta I_a/I_a$ on B_x .²⁶⁾ (d) Stability of ΔL_y at $B_x = 3.0$ mT. All measurements were performed at $V_g = 65$ V, $V_f = 10$ V, and $V_a = 700$ V.

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