Thermal Effects of Single Silicon Tip Emitters with Various Tip Radii

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Abstract

To investigate thermal effects of silicon field emitter, we fabricated and characterized single silicon tips with various tip radii, which generate different joule heating. Through I-V and stability tests, the changes of emission characteristics and tip structures due to different tip heating were observed and discussed. From the results, we confirmed that the changes of emission characteristics due to thermal effects in silicon emitter could occur at relatively small emission currents and concluded that the thermal effects should be also considered under normal operation condition above 1 μA.

1. Introduction

Theoretical studies on thermal instability in field emitter have noticed that thermal effects are negligible under normal operation condition[1-3]. However, the theoretical results can be different from real emission aspects because of the difficulties in modeling asymmetry, rough surfaces, impurities of tip, and so on[4-6]. Thus, the experimental studies on thermal effects, as well as the theoretical studies, are required.

In silicon tip, the dominant heating mechanism affecting tip apex temperature is joule heating which is inversely proportional to the square of tip radius[2]. Thus, we fabricated single silicon tips with various tip radii and investigated the changes of emission characteristics depending on tip radii during electrical operation. Also, the tip shapes before and after the operation were examined by SEM to observe the geometrical changes.

2. Fabrication

The fabrication process of single silicon tip is shown in Figure 1. As a starting material, a boron-doped (100)-oriented silicon wafer with a resistivity of 25 ~ 35 Ω · cm was used. An n-type well with the concentration of about 10^{20} atoms/cm^2 and the junction depth of about 4 μm was formed by phosphorus diffusion. A 550 nm-thick oxide layer was thermally grown at 1000 °C in wet O_2 ambient. Then, the oxide layer was patterned into an 1.4 μm-diameter disc that serve as the mask for subsequent etching using a conventional mask aligner and a reactive ion etcher (RIE). An 1.4 μm-thick silicon was etched by RIE in the condition of SF_6, 150 mTorr, 25 sccm. And then, the exposed surface was thermally oxidized to sharpen the silicon tip at 950 °C in wet O_2 ambient. At this time, the thickness of the oxide layer was precisely controlled to adjust tip radius. Molybdenum was perpendicularly evaporated on the wafer by an E-gun evaporator in order to form the gate electrode. Then, the oxide layer was selectively removed in 7:1 BHF solution. As a result, the fabrication of gated silicon tip emitter was completed. The single silicon tip emitters with various tip radii resulted from process variation of tip mask photolithography are shown in Figure 2.

3. Results and Discussion

Electrical measurements were performed in an ultra high vacuum (UHV) chamber at the pressure of 3.8×10^{-9} Torr. The chamber was baked at 200 °C for 10 hours before measurements. The cathode was grounded, the anode was biased at + 400 V and a positive bias was applied to the gate. The distance

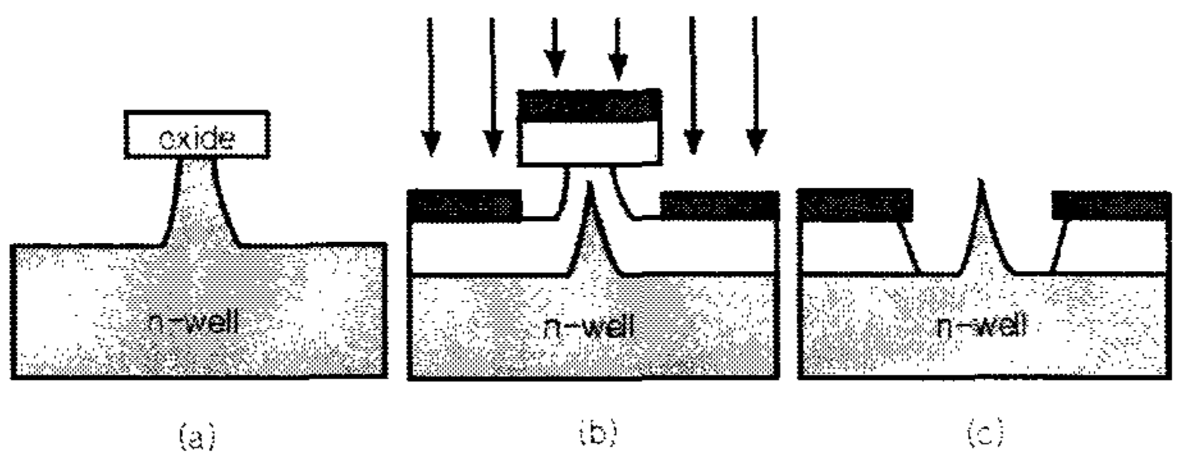
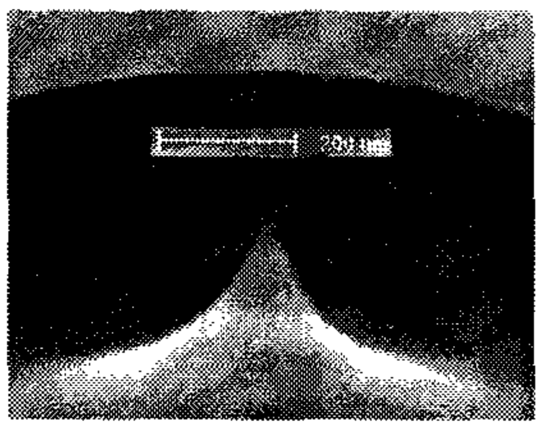


Figure 1. The process sequence of silicon tip emitter fabrication: (a) tip disc patterning and silicon etching, (b) sharpening oxidation and gate-metal deposition, and (c) lift-off.

(a) sample A



(b) sample A (expanded)

(c) sample B

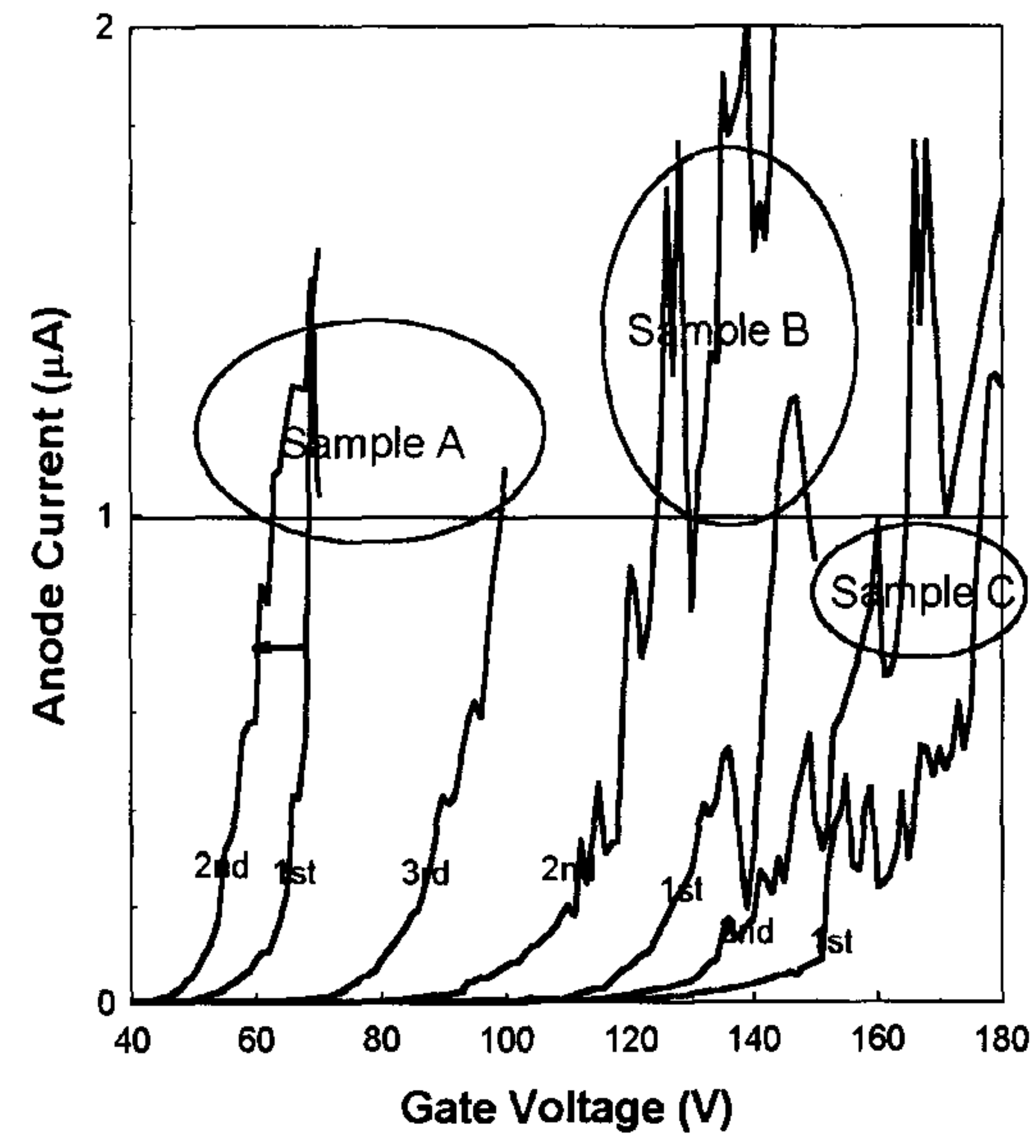
(d) sample C

Figure 2. The SEM photographs of as-fabricated single silicon tip emitters with various tip radii.

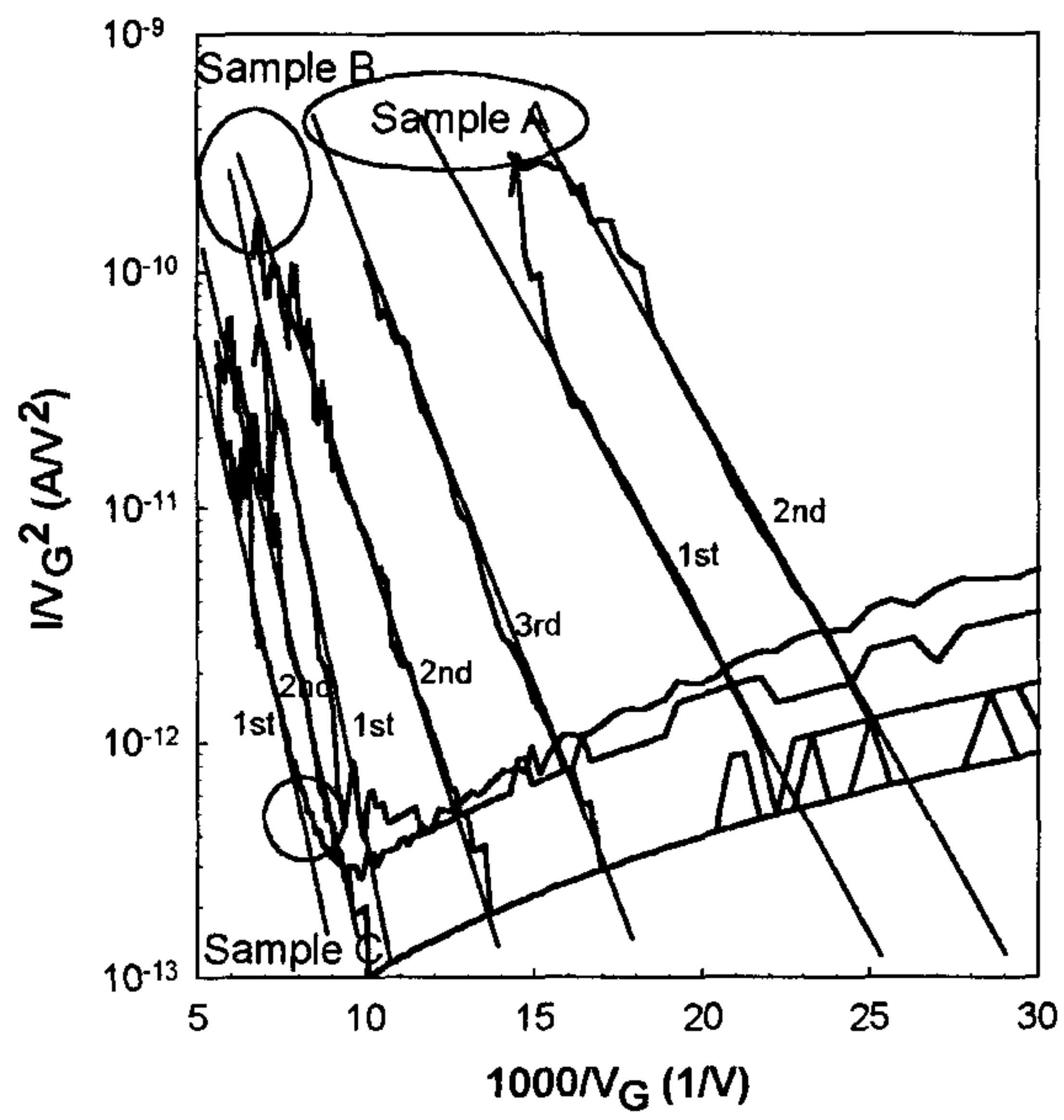
between the anode and the gate was maintained to be about 1 mm.

3.1 I-V Characteristics

In silicon tip, the amount of heating is determined by resistance component at tip apex and emission current level. Therefore, we repeatedly applied gate bias to tip, controlling the maximum bias for changing the amount of tip heating. The I-V characteristics for three samples and its Fowler-Nordheim plots are shown in Figure 3. After the exposures to the maximum currents around 3 μA, remarkable changes of emission characteristics were found. The turn-on voltage of silicon tip with small tip radius (< 20 nm) increased as the maximum current increased after the slight decrease at the first stage. The turn-on voltage of silicon tip with large tip radius (> 50 nm) consistently decreased. In SEM analysis before and after operation, although the changes in tip shapes were small in cases of samples A and B, build-up and dulling of tips were detectable. In sample C, we observed the fact that silicon at tip apex was consumed by tip evaporation at locally overheated region due to asymmetry of tip as shown in Figure 4. Also, in a special case with large tip radius, we acquired clear evidences for build-up of tip (Figure 5 (b, f)). As seen in the figure, evaporation, as well as build-up, was involved. Some molten areas in the gate metal can be considered as the phenomena by evaporation-initiated arc (Figure 5 (c~f)) because gate oxide thickness was thick enough to endure the applied bias. If those were due to oxide breakdown, the same phenomena should have equally occurred in samples A and B.

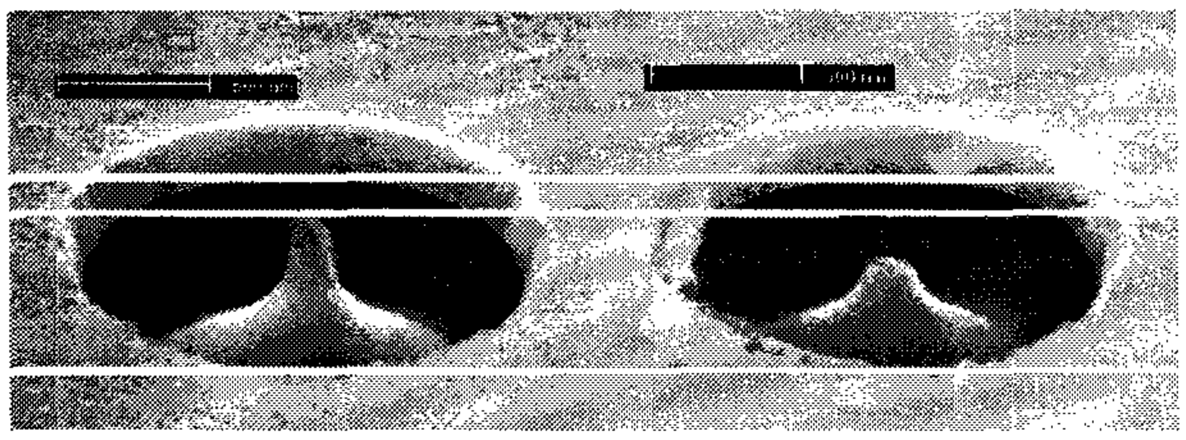


(a)



(b)

Figure 3. (a) The I-V characteristics and (b) its F-N plots for single silicon tips with different tip radii.



(a) (b)

Figure 4. The SEM photographs of sample C (a) before and (b) after I-V test.

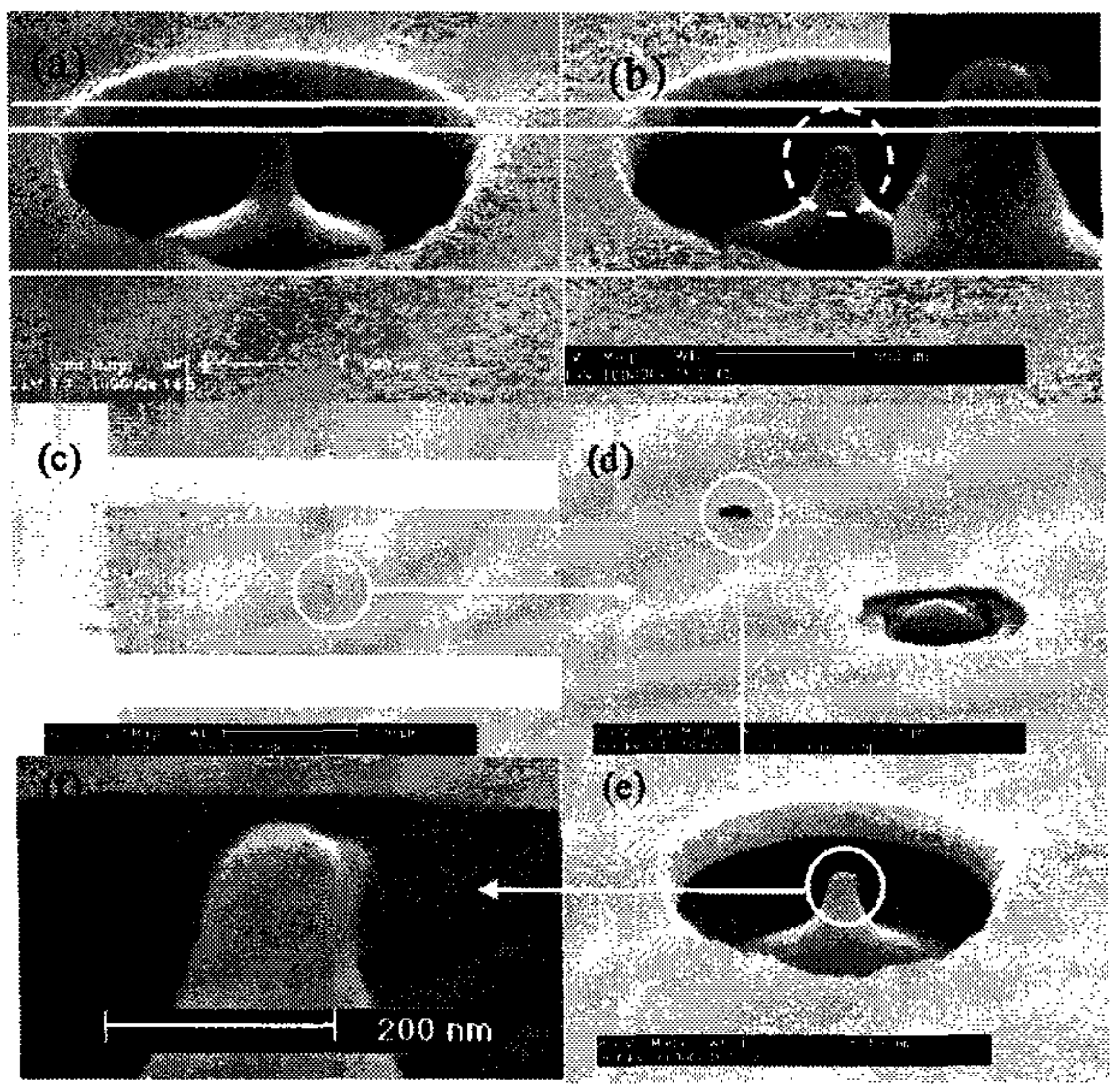
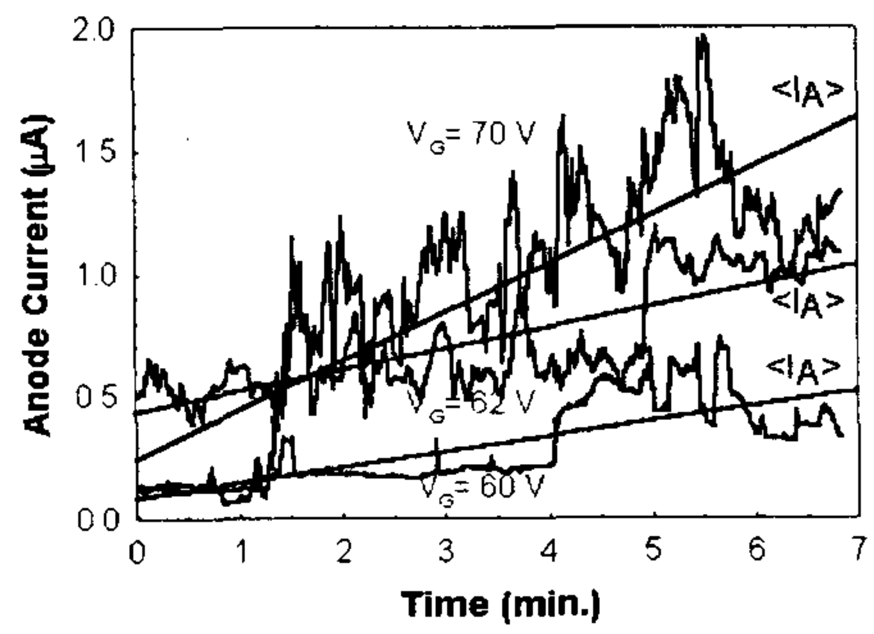
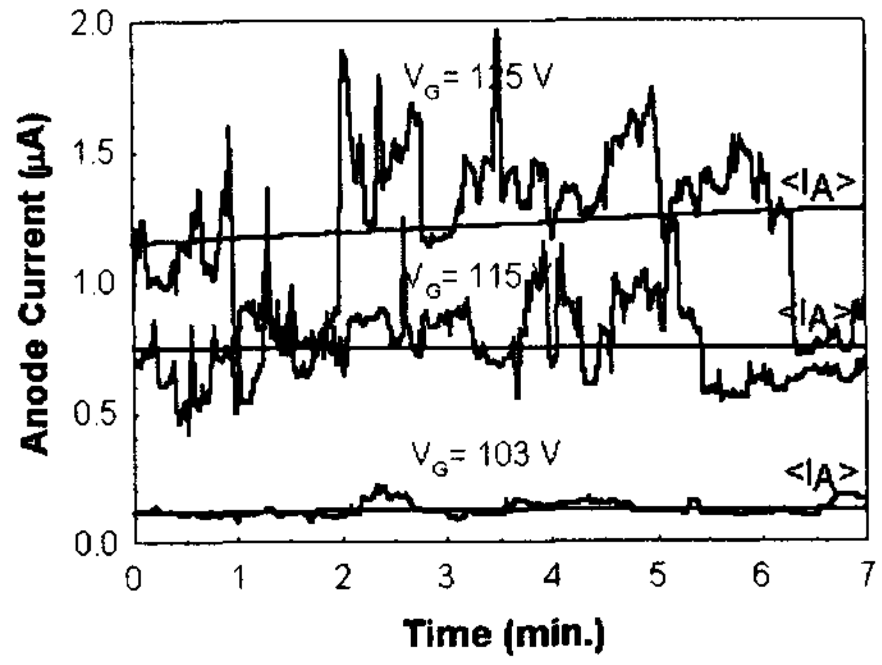


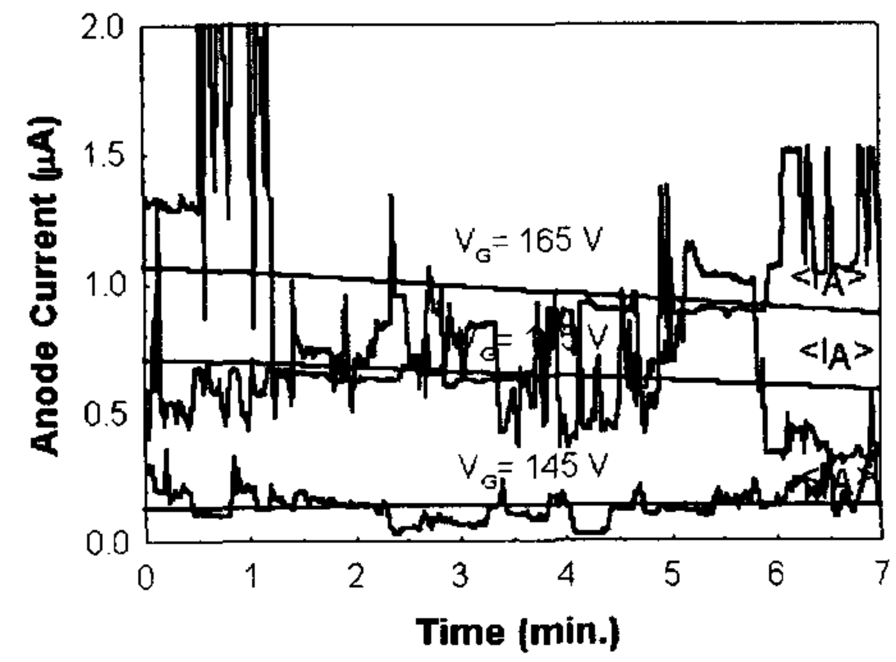
Figure 5. The SEM photographs of a single silicon tip (a) before and (b) after high current operation (~1 μA). After high current operation, silicon at tip apex was consumed, build-up of silicon tip toward gate electrode was observed, and (c~f) molten gate metal was detected. The cause of the aspects seems like arc induced by tip evaporation.



(a) sample A



(b) sample B



(c) sample C

Figure 6. The short term stability for sampls A, B, and C.

3.2 Emission Current Stability

Stability tests for each sample were carried out. Figure 6 shows the short-term fluctuations of single silicon tips for three samples. As the operation time went by, the emission current level was gradually increased for sample A, nearly fixed for sample B, and slightly decreased for sample C, respectively. As the emission current level increase, the amounts of changes for average current were also rapidly increased for sample A, slowly increased for sample B, and slowly decreased for sample C, respectively. Because the emission current level was not enough to increase the tip temperature up to melting temperature, it was thought that these phenomena was mainly resulted from desorption of impurities due to tip heating rather than build-up or dulling. In other words, smaller tip radius and higher current level generated much more tip heating, which made faster desorption of impurities.

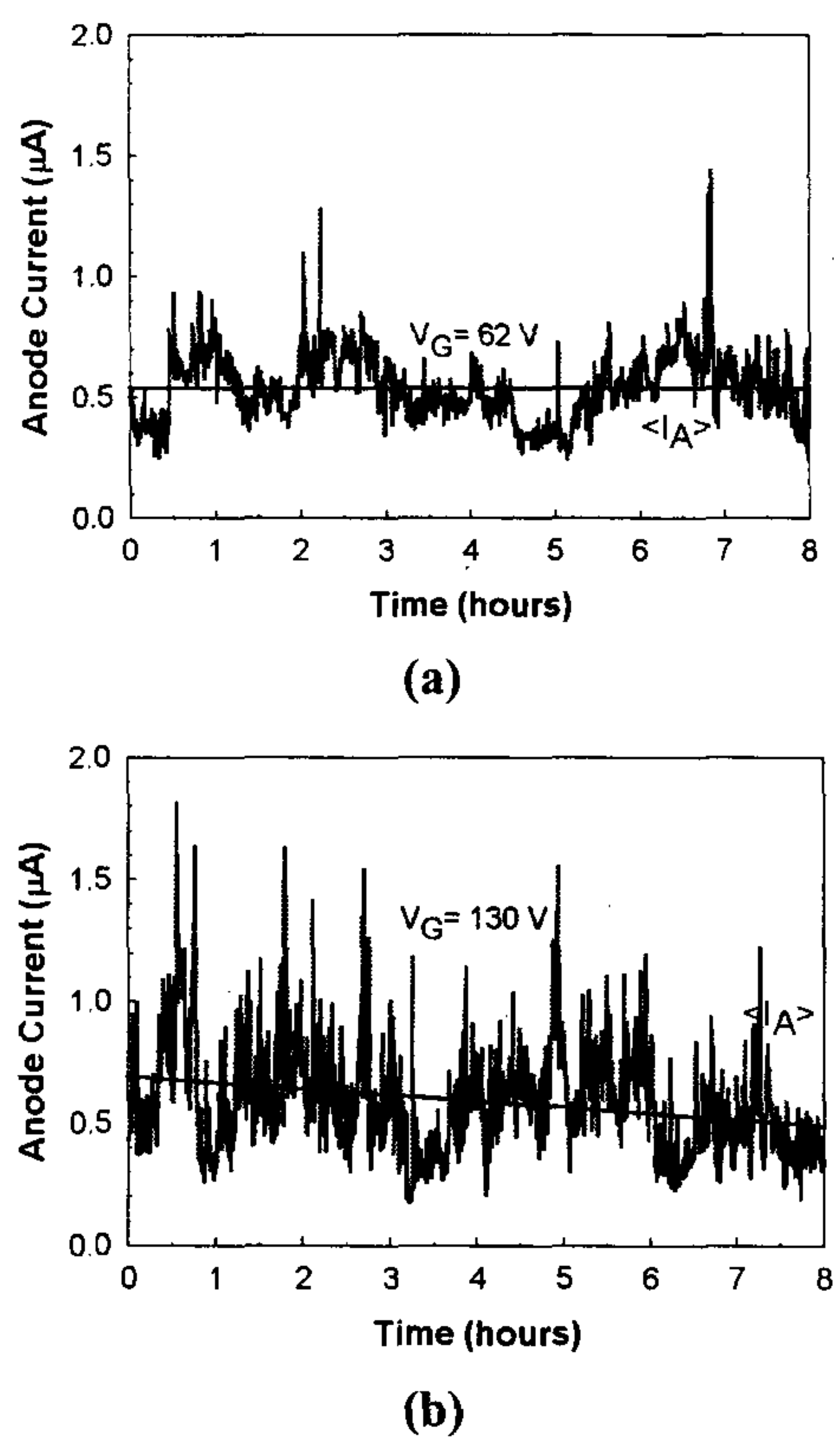


Figure 7. The long-term fluctuations for (a) samples A and (b) B.

Experiments on long-term stability for samples A and B are also performed. Before the experiments, appropriate electrical treatment for each sample was made. The long-term fluctuations were observed at the current level of about 0.5 μA during 8 hours. Figure 7 shows the emission current fluctuations for each sample. The fluctuations for the silicon tip with small tip radius treated by appropriated electrical treatment were lower and the emission currents were more stable.

4. Conclusions

To show the effects of tip heating and tip radius for emission characteristics, single silicon tips with various tip radii were fabricated and characterized. In I-V tests, remarkable changes of emission characteristics were made after the exposures to the maximum currents around 3 μA. From SEM analysis, we obtained clear evidences for build-up and evaporation of tip. In stability test, the emission current level of the silicon tip with small tip radius was gradually increased because of desorption of impurities due to tip heating. However, the emission current level of the silicon tip with large tip radius remains nearly constant because of the lack of tip heating. From the results, we confirmed that the changes of emission characteristics due to thermal effects in silicon emitter could occur at relatively small emission currents and concluded that the thermal effects in silicon tip should be also considered under normal operation condition above 1 μA.

5. Acknowledgements

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6. References

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