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Characterization of Lateral Type Field Emitters with Carbon-Based Surface Layer

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Abstract

Lateral type poly-silicon field emitters were fabricated by utilizing the LOCOS (Local Oxidation of Silicon) process. For the implementation of an ideal field emission device with quasi-zero tunneling barrier, a new and fundamental approach has used conducted by introducing an intelligent carbon-based thin layer on the cathode tip surface via a field-assisted self-aligning of carbon (FASAC) process. Fundamental lowering of the turn-on field for the electron emission was feasible through the control of both the tip shape and surface barrier height.

Keywords : FED, lateral field emitters, poly-Si, C-based surface layer, surface workfunction

1. Introduction

Field-emission devices have recently become drawn many attention for their relevant applications, such as flat-panel displays, vacuum microelectronics, electron source, RF oscillators, and vacuum sensors [1-5]. Various geometrical structures and cathode materials have been recently studied for the development of better field-emitter tips maintaining lower turn-on voltages and high stability even under high emission current densities [1], [6-8]. Research efforts in silicon-based field-emission devices are growing rapidly because of the possible reproducibility and uniformity that can be obtained from the application of highly advanced Si-based technology for the fabrication of integrated circuits.

In addition to the vertical Spindt-type field-emission devices, lateral-types are also advantageous for high-speed operation and RF applications because of their simple design and fabricating processes, easy control of electrode distances and better electrical characteristics, such as lower turn-on voltages and higher current densities [7-10]. In general, field-emitter tips must be sharp enough for low voltage operation because the local electric field near the cathode tip ends scales up with the sharpness. However, due to the severe local emission of electrons through high surface potential barrier resulting in a local heating, sharp field-emitter tips have also shown unstable emission behaviors even for the very low turn-on DC voltages. On the basis of prerequisite for the field emission devices with high current density and good stability, one of feasible ways would be to decrease the turn-on fields for field emission from the solid-state emitters. Surface barrier height of electron tunneling can be largely modified an appropriate controll of either tip shape resulting in a field-enhancement effect and/or wide bandgap surface layers on the sharp tip end resulting in a quasi-negative electron affinity [11].

In this work, we propose a promising technique for the lowering of turn-on fields for electron emission by introducing an ultra-thin carbon-based surface layer on the poly-Si cathode tip surfaces and then, comparatively demonstrating the emission behavior of sharp poly-Si tips with or without a carbon-based surface layer.

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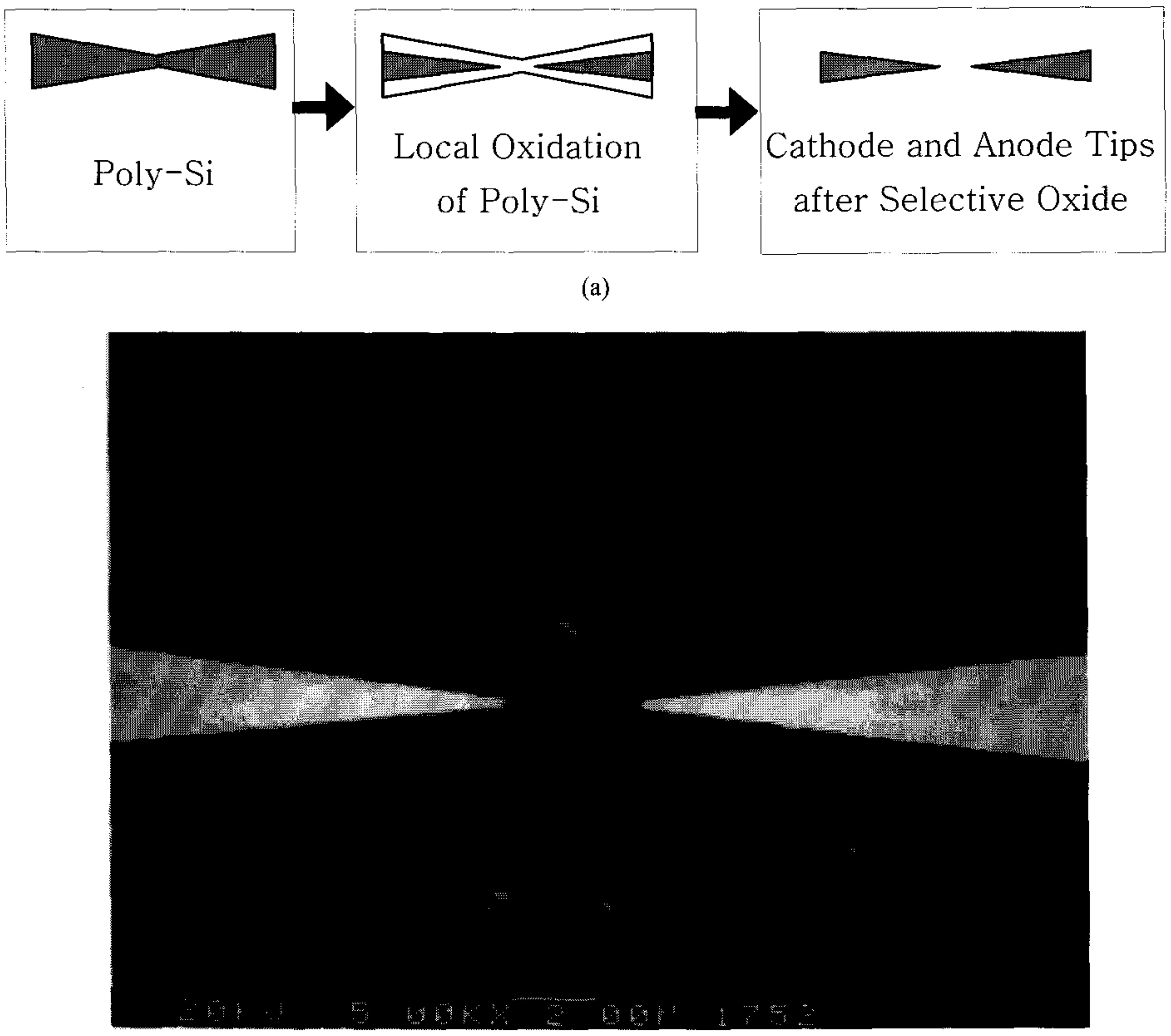


(a)

(b)

Fig. 1. (a) Key aspects of the LOCOS process resulting in sharp emitter tips and (b) SEM image of the lateral-type symmetric emitting diode.

2. Device Fabrication and Measurement

Figs. 1 (a) and (b) show the key aspects of the LOCOS (local oxidation of silicon) process resulting in well-defined, sharp emitting tips and SEM image of the lateral-type symmetric emitting diode. Typical fabrication flow was explained in detail in ref. [8-9]. An n^+-poly-Si was employed as the emitting tip with a carrier concentration of $8\times10^{20}/cm^3$, mobility of 12 $cm^2/V.s$ and sheet resistance of 15 Ω/sq. The length and end-diameter of cathode tip was about 100 μm long and 200 nm wide resulting in a probable field enhancement factor of 500-1000 and the gap distance between the sharp cathode and anode tips was only 3 μm for the measured diode pattern. Reactive carbon-related ions of 100 eV were generated using CF_4 gas and then bombarded on the opened area of polysilicon tips to modify the surface potential barrier. Initially, the surface carbons were more or less randomly distributed instead of a surface layer but, by applying an appropriate field between the anode and cathode tips, we succeed in deriving an ultrathin carbon layer via field-assisted, self-aligning of carbon (FASAC).

After a visual inspection, the devices were wire-bonded in an IC chip package and loaded into a vacuum chamber at a pressure of 6×10^{-7} torr and heated at 200 °C for 3 h to eliminate some probable contaminants near tips. Then, after the initial measurement of poor emission current-voltage behavior, a field-assisted self-aligning of carbon (FASAC) process for the emitter tip was carefully performed step-by-step to drive in surface carbon layer near the emitting tip-end. With the successful completion of the FASAC process, we could observe some dramatic changes in the electron emission behaviors resulting in not only extremely high current of few hundred μA per tip but also a highly reliable long-term stability of ± 2 % at a current of few hundred μA for a diode pattern. All of the measurements and field-assisted treatments were carried out by employing the semiconductor parameter analyzer (HP4145) and confirmed that the substrate was electrically well isolated from the tip electrodes by 500 nm-thick buried oxide.

3. Results and Discussion

Just after the incorporation of ultrathin surface carbon layer onto the poly-Si tip and Si substrate using reactive ion process, Auger electron spectra (AES) were recorded and noticeably revealed the surface species of Si peak near the kinetic energy of 70 eV, C peak near 260 eV, and O peak near 500 eV as demonstrated in Fig. 2(a). The depth distribution of each species is also checked for both Si substrate and poly-Si tip and is shown in Fig. 2(b) clearly indicating deeper incorporation of only C into the poly-Si tip area due to a micro-crystallite nature of poly-Si. At first glance, the AES carbon-spectra revealed initial surface carbons with graphite-like structure [12] or sp^2-bonded amorphous-like structure [13].

With a gradual progress of FASAC process in a simple diode structure as shown in Fig. 1(b), we can finally observe a dramatic increase in the emission current from ~1 nA to 500 μA per tip at an apparent field of only 7 V/μm as shown in Fig. 3 (a). Fig. 3(b) also shows an abrupt increase of long-term reliability in the emission tips during the operation time of 1000 min from the initial high fluctuation of low currents to the negligible fluctuation of even very high currents between 100-500 μA per emission tip as indicated at the end of each line. After the final FASAC process, no distinct change in tip shape and macroscopic morphology was observed and thus, a large increase in field enhancement factor would not be a valid factor to explain the present dramatic enhancement of emission currents. On the basis of tunneling mechanism, one may consider two other cross-linked factors; one is a huge expansion of effective emission area and the other is a great reduction of electron tunneling barrier almost down to zero. An expansion of effective emission area would be a contributing factor to some extent but it would not be a major origin of improvement in the emission performance from a sharp tip. A main driving factor for the change of emission properties should be a corresponding variation of surface barrier height prohibiting electron tunneling from poly-Si to vacuum.

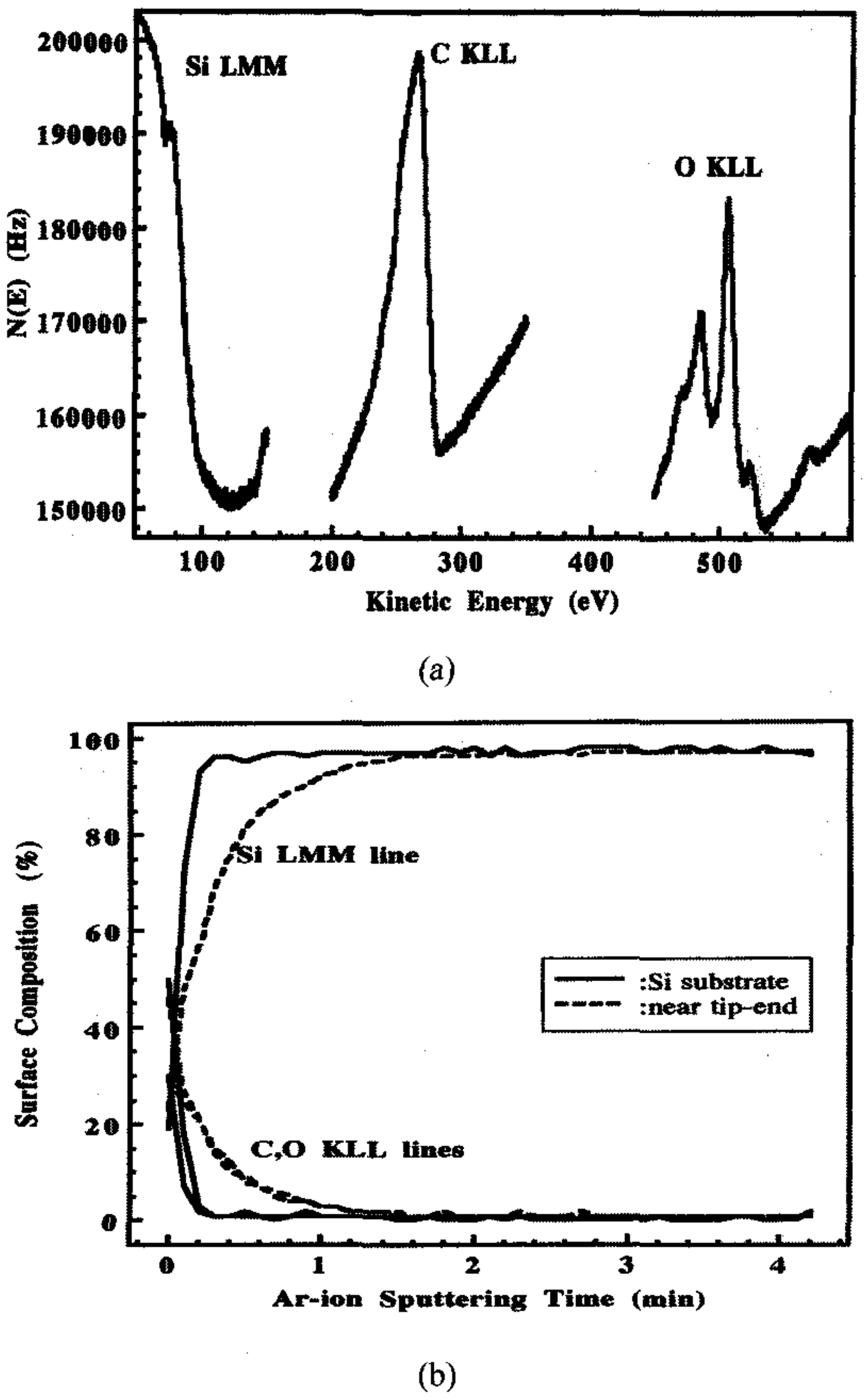
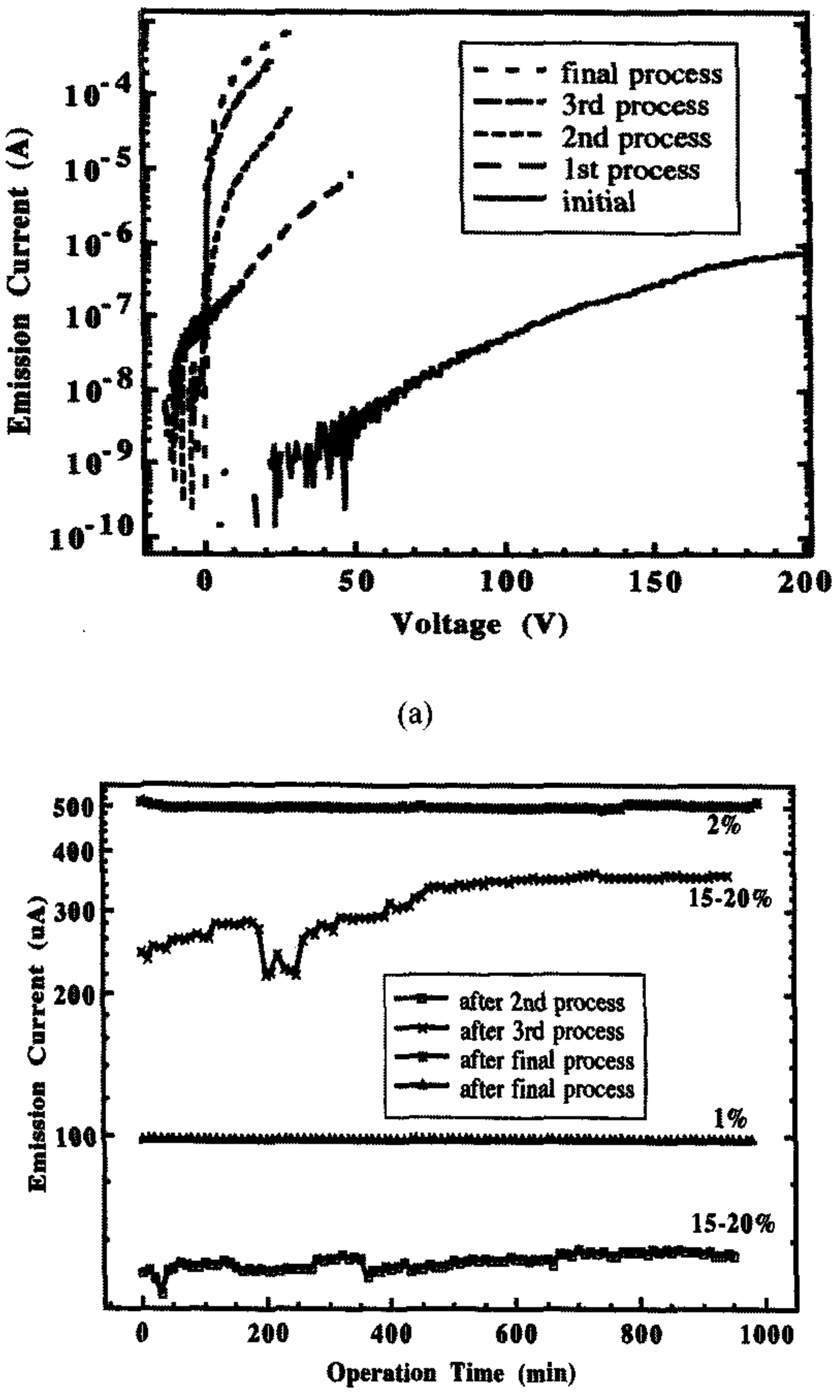


Fig. 2. (a) Initial AES spectra of poly-Si tip and Si substrate area revealing Si at 70 eV, C at 260 eV, and O at 500 eV, and (b) depth profiling of each species for both Si substrate and poly-Si tip.

To identify the physical origin of our speculation on a decreasing surface workfunction due to a strong band banding between the poly-Si and ultrathin surface layer, we carried out an AES survey for the close-evaluation of the surface composition of poly-Si cathode tip and were able to observ a clear evidence of not only a self-aligning of carbon-based surface layer near the emitter tip-surface but also a phase transformation of incorporated carbon species. Fig. 4 illustrates the corresponding AES spectra of poly-Si tip surface. The Si LMM line near 70-90 eV of the thin poly-Si layer, corresponding to the kinetic energy of a minimun mean-free path of a few monolayers, was completely attenuated by the field-assisted self-aligning of surface C-containing layer, and also, the peak shape of C KLL Auger line was changed from the initial one of Fig. 2(a) indicating a change in the chemical environment around carbon atoms. A detailed analysis of the AES carbon-spectrum indicated a phase transformation of initial surface carbons into SiC-like structure or sp^3-bonded amorphous-like structure. Without any charging phenomena, the energy positions of final Si, C, and O Auger peaks were all shifted into higher kinetic energies by 10-30 eV due to the fundamental lowering of surface potential energy [13].



(a)

(b)

Fig. 3. (a) Electron emission current-voltage behavior of symmetric sharp poly-Si tip with the progress of field-assisted self-aligning of C-based surface layer (FASAC) on tip surface and (b) the corresponding long-term stability of field-treated emission diode.

In connection to gradual surface engineering using a FASAC technique, the traditional Fowler-Nordheim (FN) tunneling equation for the electrons through the surface potential barrier would not be applied for the modeling of the field emission behavior of symmetric sharp lateral poly-Si diode-type tips. As an example of model fitting, however, the initial emission current-field behavior from an as-fabricated tip was in good agreement with the FN model as shown in Fig. 5(a). From the FN modeling, we can consistently extract some key parameters governing the emission of electrons from a poly-Si tip to vacuum via a surface-carbon layer. Under an effective field of F (V/cm) between the surface potential barriers of ϕ (eV), the emission current density of J (A/cm^2) was analytically modeled by Fowler-Nordheim [14];

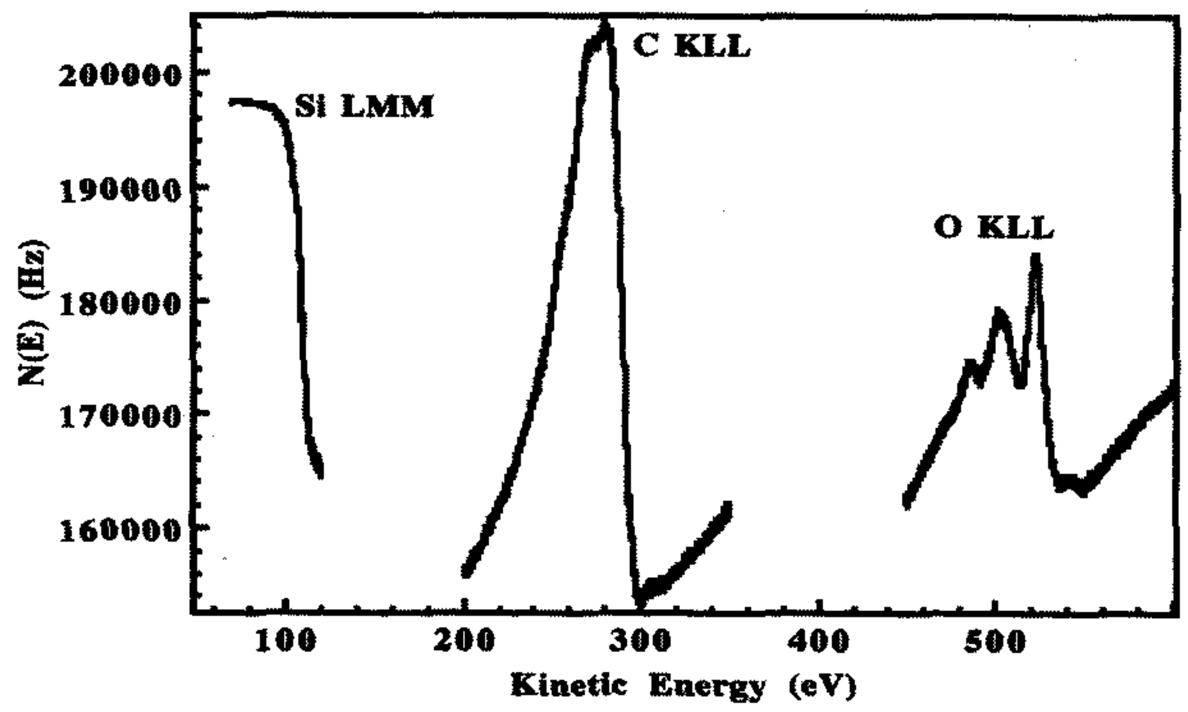


Fig. 4. AES spectra of field-treated poly-Si tip surface resulting in self-aligning and phase change of surface C-containing layer.

$$J \approx 1.0\times10^{-6}\frac{1}{\phi}\times F^2\times\exp(-\frac{(6.5\times10^{7}\times\phi^{3/2})}{F}) \tag{1}$$

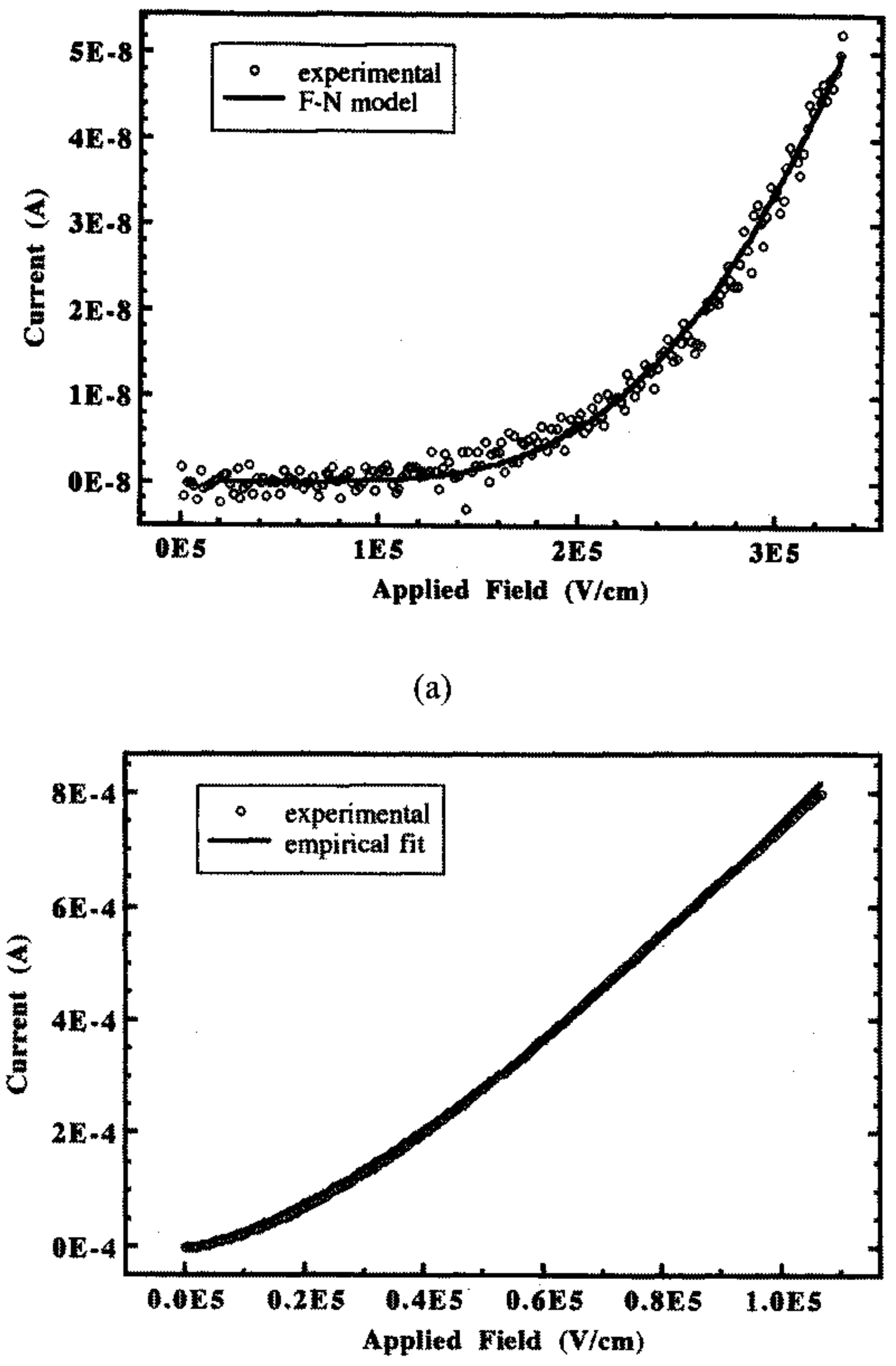
Since the gap distance between two the tips was 3 μm wide, the effective field can be defined as a function of an applied field of $F_o = \frac{V}{3\times10^{-4}}(V/cm)$ by considering a constant field enhancement factor β; $F = \beta F_o(V/cm)$. Then, with the effective emission area of $\alpha(cm^2)$, the total current can be further modeled as follows;

$$I \approx 1.0\times10^{-6}\frac{\alpha\beta^2}{\phi}\times {F_o}^2\times\exp(-\frac{(6.5\times10^{7}\times\phi^{3/2})}{\beta F_o}) \tag{2}$$

FN modeling of initial I-F data was in the best agreement for the linked input parameters;

$$1.0\times10^{-6}\frac{\alpha\beta^2}{\phi} = 2.16065\times10^{-18}(Acm^2/V^2) \tag{3}$$

$$\frac{6.5\times10^{7}\times\phi^{3/2}}{\beta} = 5.23898\times10^{5}(V/cm) \tag{4}$$



(a)

(b)

Fig. 5. Model fitting of emission current-field behavior measured from a single poly-Si diode-type emitter; (a) initial behavior and (b) after final FASAC process.

Here, we can accurately determine the key parameters of surface workfunction and effective emission area by using a probable field enhancement factor between 500-1000 for the present tip design. Upon considering the critical turn-on field of 0.5 V/Å [15], field enhancement factor of 500-1000 is seen to be high enough for the observation of turn-on at an applied field of about 1.5×10^{-3} V/Å corresponding to an effective field of 0.75-1.5 V/Å. A determined surface workfunction was either 2.6 eV for $\beta = 500$ or 4.1 eV for $\beta = 1000$. In addition, the obtained emission area was $1\text{-}2\times10^{-17}$ cm^2 that is much smaller than the designed tip area of Fig. 1(b), but such a large difference is due to the deviation between the FN model for the plat emission area and measured current from a sharp tip.

Once the tip surface was modified by FASAC process without a distinct change in the tip shape, the original FN model was not applicable for the modeling of measured current-field properties and, after the final process, we could derive a valid relationship indicating almost zero or quasi-negative surface workfunction. Fig. 5(b) shows the modeling of the final current-field behavior by a modified FN equation including a field screening or space charge effect;

$$I \approx 1.0\times10^{-6}\frac{\alpha\beta^2}{\phi}\times F_o^{1.406}\times\exp\left(-\frac{(6.5\times10^7\times\phi^{3/2})}{\beta F_o}\right) \qquad (5)$$

The best fit was obtained for the surface workfunction of quasi-zero and the emitting area remained un-changed from the initial one for the same field enhancement factor of 500-1000. This observation of quasi-zero surface workfunction from poly-Si tip with C-based surface layer would be comparable to the previous reports on the development of quasi-zero surface barrier from tetrahedrally bonded amorphous carbon [13] and also quasi-negative surface workfunction from a metallic surface with an ultrathin wide bandgap semiconductor films [11].

4. Conclusions

A carbon-related surface layer was uniformly incorporated onto the poly-Si cathode-tip surface via the field-assisted self-aligning of carbon (FASAC) process and the initial phase of carbon was a graphite-like or sp^2 bonded amorphous structure resulting in a surface workfunction of 3-4 eV. With the FASAC process, the surface carbons were redistributed onto the tip surface and also transformed into SiC-like or sp^3 bonded amorphous structure resulting in a quasi-zero or quasi-negative surface workfunction. Once an ultrathin C-based surface layer was derived in on a metallic tip surface, we could observe promising emission behavior from a single tip such as a high current density, low turn-on voltage, and negligible fluctuation of emission current even at ~100 μA over a long-term operation due to a set-up of quasi-zero surface workfunction.

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