Effect of carbon coating on electron field emission from polysilicon

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Carbon films deposited at relatively low temperatures were studied as a coating for polysilicon substrates to provide enhancement of the electron field emission. Undoped and phosphor doped polysilicon substrates were coated by carbon films grown by a very high frequency chemical vapor deposition process. Critical process parameters include substrate temperature of 225 °C, pressure of 56 mTorr, loaded power of 2 W/cm^2, and discharge frequency of 56 MHz. The substrates were pretreated prior to film deposition, and bias enhanced nucleation was performed in hydrogen/C_6H_{14} plasma. A carbon layer was grown to a thickness of 700 nm. Field emission measurements were performed in an ultrahigh vacuum chamber equipped with an electron gun, a carousel for five samples, and a Faraday cup. A multigrid quasispheric energy analyzer was used for Auger electron spectroscopy and electron energy loss spectroscopy characterization. Additionally, before and after field emission measurements, the secondary emission coefficient σ was measured by a scanning electron beam, which provided a two-dimensional σ map of the sample surface. The field emission current was measured in a diode configuration using a spacer thickness of 45–55 μm through a current collection window 2×5 mm^2. Emission current–voltage curves were measured from three different regions of every sample by shifting the current collection window over the sample. A surface conditioning effect was observed, resulting in stabilization and better reproducibility of the emission current–voltage characteristics. The most significant changes in emission characteristics were observed in undoped polysilicon substrates with carbon coatings. Low deposition temperatures make this coating process very attractive because of its compatibility with addressing circuitry based on either silicon or poly-, microcrystalline, or amorphous silicon. *© 2000 American Vacuum Society.* [S0734-211X(00)08502-4]

I. INTRODUCTION

Coating of the surface of silicon or of poly-, microcrystalline, or amorphous silicon by carbon films deposited at relatively low temperatures can provide effective field emission and it is very attractive because of its compatibility with associated circuitry fabricated on these substrates. Improvement of field emission characteristics in Si tips and flat silicon samples coated with non-diamond carbon film has been reported.[1–3]

Polysilicon is used for driving integrated circuits. It would be of interest to study the possibility of improving the emission properties of polysilicon by the deposition of carbon layers. Moreover, dependence of the threshold field on the doping of polysilicon layer could be expected.

In this work emission characteristics of nondoped and *n*-doped polysilicon were studied. The effect of nondiamond carbon coating on polysilicon emission properties was also investigated.

II. EXPERIMENT

Polysilicon coated wafers were used as substrates. Nondoped polysilicon substrates (denoted Si1) were doped with phosphorus at different doping levels: $4-6\times10^{18}$ cm^{-3} (denoted Si2) and at $0.8-2\times10^{20}$ cm^{-3} (denoted Si3). All substrates were coated with carbon films on the same run. The carbon films were grown by very high frequency (VHF) chemical vapor deposition (CVD), described in Ref. 4 under the following conditions: substrate temperature $T_s=225\,°\mathrm{C}$, pressure $P=56$ mTorr, power $W=2$ W/cm^2, frequency $f=56$ MHz, gas mixture $R1=7\%C_6H_{14}+93\%H_2$, flow $Q=27$ sccm. Prior to deposition, the substrates were pretreated in hydrogen plasma and bias enhanced nucleation (BEN) was performed. The carbon layer was 700 nm thick. The area of all samples was approximately 1 cm^2. Emission was measured in the setup schematically shown in Fig. 1(a). An ultrahigh vacuum (UHV) chamber, equipped with an electron gun and a multigrid quasispheric energy analyzer, a carousel for five samples, and a Faraday cup, was used. The multigrid quasispheric energy analyzer was used for Auger electron spectroscopy (AES) and electron energy loss spectroscopy (EELS) characterization. Before and after the measurements, the secondary emission coefficient σ was measured by a scanning electron beam that provided a two-dimensional (2D) σ map of the sample surface. The configuration of the electrodes used for the emission current measurements is shown schematically in Fig. 1(b). The current was measured

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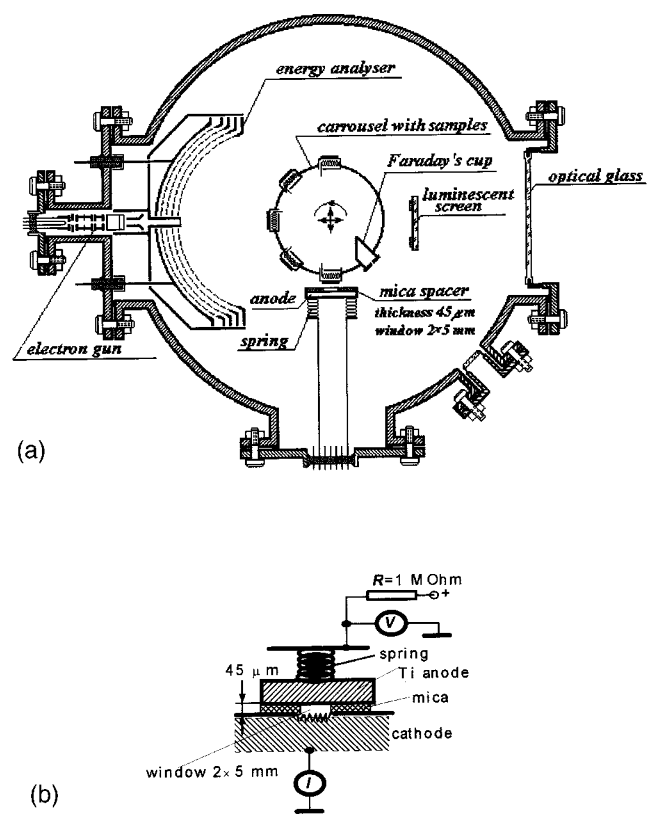

FIG. 1. Diagram of the setup for the emission measurements: (a) UHV chamber for emission measurements and material characterization and (b) schematic of the emission current–voltage measurements.

at a base pressure of 10^{-9} Torr in a diode configuration with 45–55 μm spacing and an anode area of 2×5 mm^2.

III. RESULTS AND DISCUSSION

Emission current–voltage ($I-V$) curves were measured up and down several times from three different regions of each sample (by shifting the current collection window over the sample surface). On a few occasions, high voltage breakdown (microarcing) was observed; after this the region was excluded from further measurements and analysis. A surface ''conditioning'' effect (without arcing) was observed in some samples, and then the $I-V$ curves became stable and reproducible. The effect of surface conditioning and microarcing can be clearly seen in secondary electron emission images (SEEIs) measured before and after emission measurements. An example of a SEEI for nondoped polysilicon (sample Si1) without carbon film is shown in Fig. 2. As seen in Fig. 2(a) before the emission measurements the secondary electron emission coefficient σ varies slightly across the sample surface σ=0.95/1.05. After the emission measurements, which were carried out in three different regions of the sample, in some places a significant change in σ occurred [see Fig. 2(b)]. For the first part of the sample, in the beginning there was no emission current up to 1.5 kV. Then microarcing occurred and a stable current–voltage characteristic was observed. In Fig. 2(b) one can see spots in the lower and middle parts of the first region where σ has changed to σ=0.85. These spots most likely correspond to areas of microarcing and may be where the emission current came from. For the second emission measurement region the same conditioning procedure was observed. Spots at the upper part of the region in the SEEI, where σ has changed to σ=0.8, can be also attributed to microarcing. For the third region a stable and reproducible $I-V$ characteristic was measured from the very beginning. No microarcing or conditioning and also no change in the SEEI were observed.

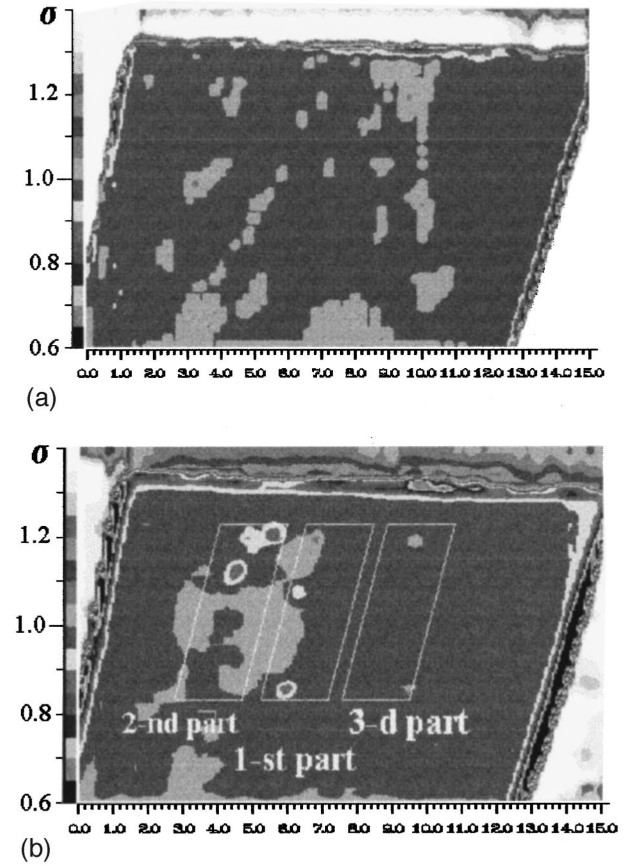

FIG. 2. Secondary electron emission images of sample Si1 (a) before and (b) after emission measurements.

Doping of polysilicon by phosphorus changed the SEEIs. The secondary electron emission coefficient became more nonuniform across the sample surfaces. This effect is more pronounced for the more doped Si3 sample. The value σ did not significantly change for the middle doped Si2 sample and it slightly increased from σ=0.95/1.05 to 0.95/1.15 for sample Si3.

Carbon film coating changed σ for all samples. For the nondoped polysilicon Si1 carbon film coating the secondary electron emission coefficient was lowered, from σ=1 to 0.3. For the middle doped Si2 sample the value of σ was 0.5, and for most doped Si3 sample, σ=0.95/1.1. For sample Si3 with carbon film σ was not uniform across the surface, the same as for the sample without the film. Thus, the secondary electron emission coefficient of the carbon film coated samples increased with an increase of the polysilicon doping level. There may be two reasons for such phenomena. First, carbon

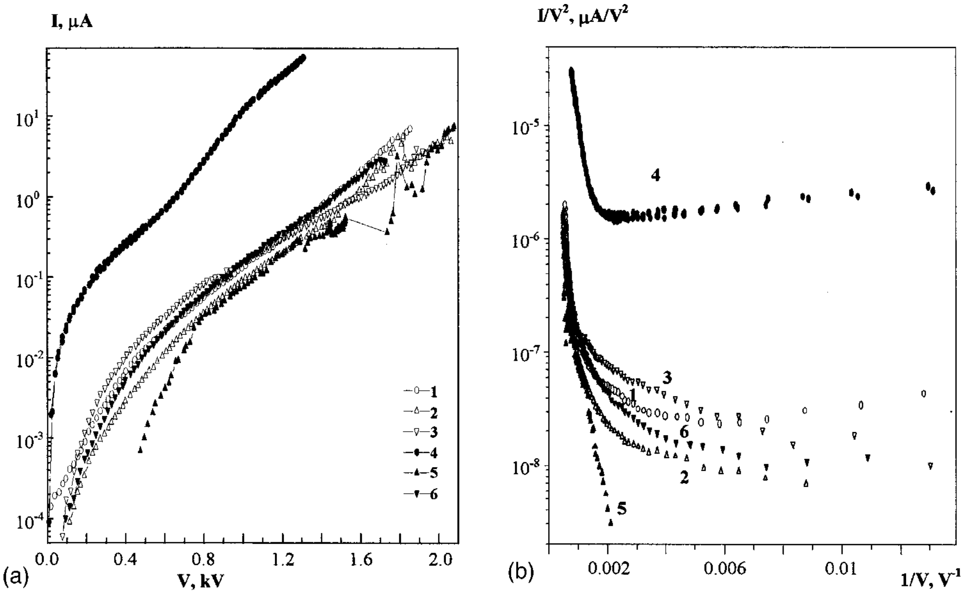

FIG. 3. Emission current–voltage curves for different polysilicon substrates on (a) semilog and (b) Fowler–Nordheim scales. (1) Si1, (2) Si2, (3) Si3, without carbon coating; (4) Si1, (5) Si2, (6) Si3, with carbon coating.

film may be porous and that is more likely for sample Si3 which demonstrates almost the same nonuniformity and σ value both with and without carbon film. Second, phosphorus doping lowers the polysilicon work function. Electrons can easily tunneling into carbon film and then through the local states in band gap to the film surface.

Figure 3(a) shows $I-V$ curves for different polysilicon substrates coated by the same carbon film in comparison with uncoated ones. Nondoped polysilicon demonstrates low turn-on field $E_t=4$ V/μm emission. Doping polysilicon with phosphorus did not significantly change the emission characteristics. All changes for sample Si1, Si2, and Si3 without carbon film were within the range of variations in different regions of one sample.

Carbon film coating significantly changed the emission characteristics of nondoped sample Si1. A turn-on field decrease from $E_t=4$ to 1 V/μm and higher current were observed for the sample with the film at the same voltages. Also, this coating significantly improved the reproducibility of the emission currents. For doped samples coated with the film, the emission properties changed slightly. There was a turn-on voltage increase from $E_t=4$ to 4.2 V/μm for sample Si2 and from $E_t=4$ to 9 V/μm for sample Si3 with the carbon film deposition. Deterioration of the emission properties of doped samples coated with the film can be explained if we take into account the interfacial layer between the carbon film and the surface of the polysilicon, which may block to some extent electron current from the polysilicon. This layer may be a ''bottleneck'' for emission current in structures with carbon films.[5] If during the doping procedure some impurities are present on the polysilicon surface, then they may react with the film. This compound may be a limiting factor for low turn-on voltages. The higher the doping level the more pronounced the effect of the intermediate layer. On the other hand, the interfacial layer between the nondoped polysilicon and the carbon film may have formed in some other way (conditions) and may be the reason for the improvement of the emission characteristics of sample Si1 with the film.

Emission current–voltage curves for the same set of samples on a Fowler–Nordheim scale are shown in Fig. 3(b). One can see the nonlinear behavior of the curves. It means that Fowler–Nordheim law is not correct for all ranges of the field studied and that the emission mechanism is more complicated than electron tunneling from metal through the surface barrier to vacuum.

IV. SUMMARY AND CONCLUSIONS

In this work emission properties of nondoped and phosphorus doped polysilicon, with and without carbon film coating, have been studied. The effect of doping with phosphorus on polysilicon emission characteristics and the influence of nondiamond carbon film coating prepared by VHF CVD at relatively low temperatures on the emission characteristics of nondoped and *n*-doped polysilicon have been observed.

The main results for polysilicon without carbon film coating were as follows.

(1) Polysilicon demonstrated a low turn-on electric field ($E_t=4$ V/μm for $I=10^{-8}$ A/cm^2) emission characteristics. Current–voltage curves for all the samples studied can be fitted by Fowler–Nordheim law only in a high voltage region. This indicates that there is a more complex mechanism of emission.

(2) Doping with phosphorus did not significantly change the emission characteristics of polysilicon.

For polysilicon substrates coated with carbon film the main results are as follows.

(1) Carbon coating on nondoped polysilicon (sample Si1) significantly improved the emission characteristics. The

turn-on field decreased to $E_t = 1$ V/μm and the saturation current was achieved at lower voltages.

(2) For doped samples carbon coating resulted in an increase of the turn-on field for the samples with carbon coating. This effect is more pronounced for the sample with a lower doping level.

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