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Diagnostics of neutral species in the low-angle forward-reflected neutral beam etching system

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Abstract

The reactive ions extracted from an ion gun were neutralized by reflecting the ions at the angle of 5° on the reflector installed in front of the ion gun. Their neutralization characteristics were investigated for SF_6 as a function of acceleration voltage and RF power of the ion gun. When the ion current density was measured as a function of acceleration voltage and RF power of the ion gun using a Faraday cup for both with and without the reflector, the ion current density measured with the reflector was drastically decreased to 99.7% compared to those measured without the reflector suggesting the neutralization of most of the reflected ions. The reactive ions extracted from the ion gun were SF^+, SF_2^+, SF_3^+ and SF_5^+. After the reactive ions were reflected at the reflector, the species were neutralized and changed to F_2, SF, SF_2, SF_3 and SF_5. The increase of acceleration voltage of the ion gun increased the lower mass peaks such as SF_2, SF and F_2 and decreased the higher mass peaks such as SF_3 and SF_5 suggesting the formation of lower mass neutrals at the reflector by the cracking and neutralization of the higher mass ions such as SF_3^+ and SF_5^+. The formation of F_2 was significant with the increase of the acceleration voltage.

Keywords: Neutral beam; Quadrupole mass spectrometer; SF_6

1. Introduction

Charge-induced damage during the plasma etching is one of the biggest problems that has to be solved for the deep sub-micron semiconductor devices as well as future nano-scale devices. To avoid the charge-related damage, several low-damage processes have been proposed [1–6] and one of the techniques to avoid the problem is to use neutral beam.

Neutral beam can be fabricated with various methods and, in previous studies, the low-angle forward-reflected neutral beam technique has been developed, where all reactive ions extracted from an ion gun are reflected on a flat surface (a reflector) with 5–15° to produce near-parallel radical beam flux [7–9]. Using the low-angle forward-reflected neutral beam technique, photoresist and SiO_2 could be etched anisotropically without charging the surface of the samples using O_2 and fluorine based gases such as CF_4, SF_6, NF_3, etc., respectively, [10,11]. Also, using a capillary hole type reflector designed to match 1:1 to the grid holes of the ion gun instead of flat surface, higher flux of the neutrals, therefore, higher neutral beam etch rates could be obtained. Even though the anisotropic etching could be accomplished using the neutrals formed by the low-angle forward-reflected neutral beam technique, the characteristics of the neutral beam such as the formation of neutrals at the reflector, neutral species, etc. were not investigated.

In this study, the characteristics of the neutral beam formed by the low-angle forward-reflected neutral beam techniques were investigated using a Faraday cup and a quadrupole mass spectrometer to understand the mechanism of neutral beam formation. Using the Faraday cup and the quadrupole mass spectrometer, the degree of neutralization and the change of reactive species after the reflection at the reflector were investigated, respectively, as a function of ion gun acceleration voltage for SF_6.

2. Experimental

A low-angle forward-reflected neutral beam source, which is composed of a RF ion gun and a reflector was used to form a neutral beam. A schematic diagram of

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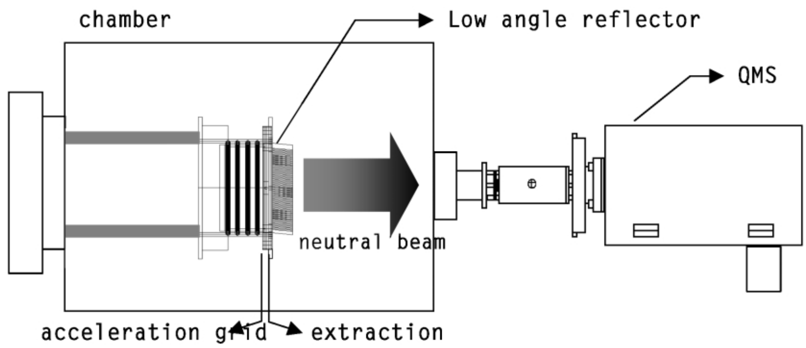


Fig. 1. Schematic diagram of the experimental system for the neutral beam generation and its measurement.

the experimental system for the neutral beam and its measurement is shown in Fig. 1. The ion gun was a homemade two-gridded inductively coupled plasma source and 7–10 sccm of SF_6 or Ar was flown to the ion gun. With the gas flow rates, the main chamber pressure was remained near 0.13 Pa. The RF power applied to the plasma source was from 500 to 700 W with a radio frequency of 13.56 MHz. The ions from the plasma source were extracted using the two-grid assembly and potentials ranging from +100 to +500 V (Va) were applied to the grid located close to the source (accelerator grid) and −50 V to the grid located outside of the source (extractor grid). The reflector was made of a perforated aluminum block where the axes of the holes in the reflector were fabricated to have 5° angle with the ion beam direction. The holes in the reflector were 1:1 matched to the holes of the grids of the ion gun. The depth and diameter of the holes in the reflector were optimized to reflect all of the parallel ions extracted from the ion gun, therefore, to neutralize the extracted ions.

The ion currents extracted from the ion gun and those emerged without neutralization at the reflector were measured using a Faraday cup as a function of the acceleration voltage of the ion gun and RF power. Homemade Faraday cup with the area of 0.196 cm^2 was used in the experiment. The Faraday cup was located to have normal incident angle with the beams and 5 cm apart from the ion gun. The current generated by the ions collected at the Faraday cup was measured by a digital multimeter (Keithley: 195A). The quadrupole mass spectrometer (Hiden Analytical Inc. PSM501) was also installed in front of the reflector and approximately 48 cm apart from the ion gun. The chamber pressure of the quadrupole mass spectrometer was less than 6.7×10^{-5} Pa. Ion species were monitored without turning on the ionizer of the mass spectrometer while neutral species were monitored with the ionizer turned on at 20 V. Ion energy distributions of Ar^+ and SF_3^+ were also investigated using the ion energy analyzer in the mass spectrometer for various acceleration voltages of the ion gun.

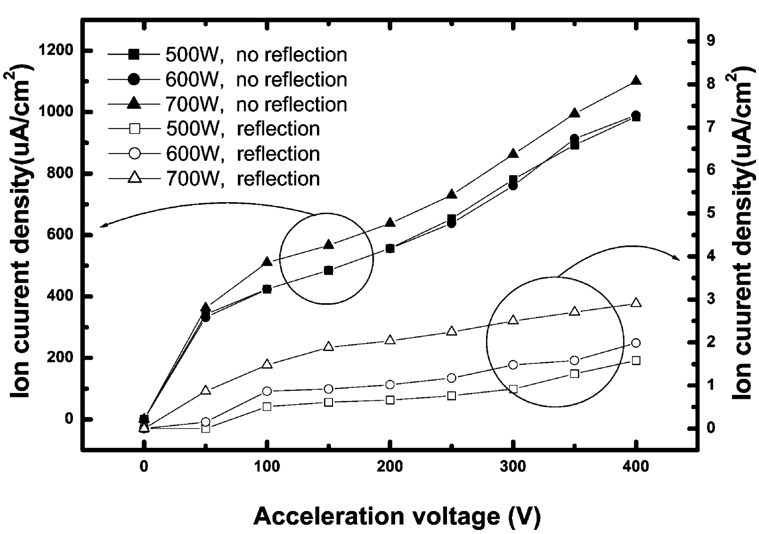


Fig. 2. Ion beam current density as a function of ion gun acceleration voltage and RF power with/without the reflector. (Distance between reflector and Faraday cup, 5 cm; SF_6 flow rate, 7 sccm.)

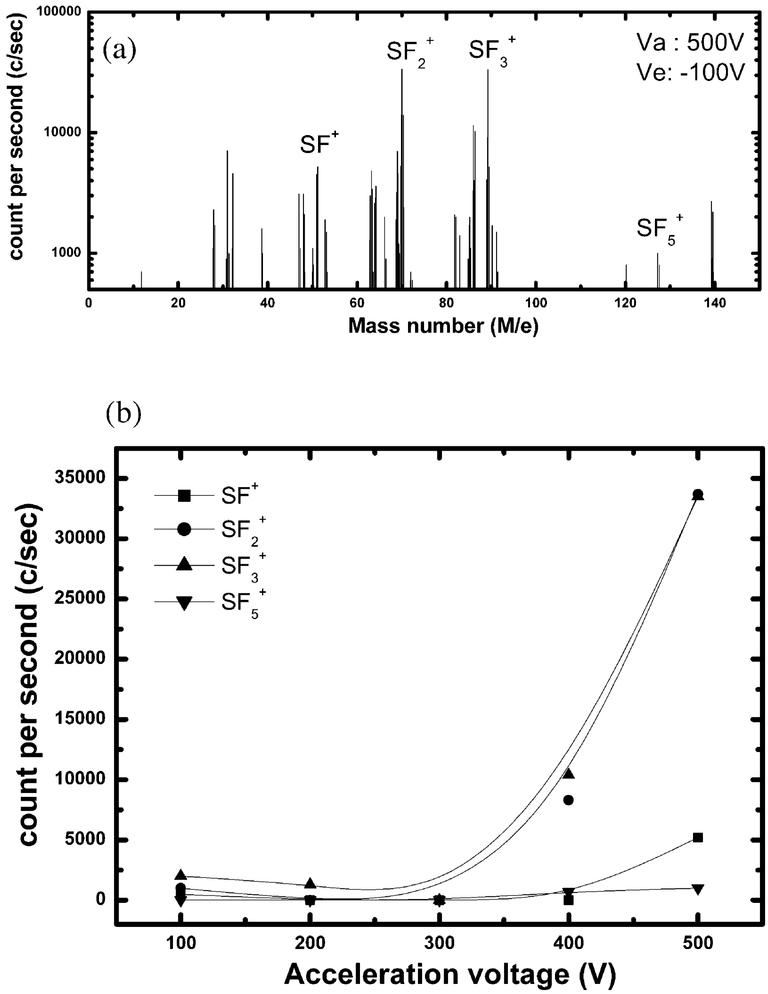


Fig. 3. (a) Ion mass spectrum of SF_x^+ ion species without the reflector for 500 V of the acceleration voltage. (b) Ion peak intensities of SF_x^+ ion species measured by a quadrupole mass spectrometer without the reflector as a function of acceleration voltage. (Extraction voltage, −100 V; SF_6 flow rate, 10 sccm.)

3. Results and discussion

Fig. 2 shows the effect of RF power and acceleration voltage of the ion gun on the ion current density with and without the reflector measured using a Faraday cup located at 5 cm apart from the ion gun to investigate the degree of neutralization by the reflector. RF power to the ion gun was varied from 500 to 700 W and the voltage to the ion gun and acceleration grid from 0 to 400 V. The voltage to the extraction grid was kept at −100 V and 7 sccm SF_6 gas was used. As shown in the figure, the ion current density measured with and without the reflector increased with the increase of acceleration voltage and RF power, however, the ion current density measured with the reflector was significantly lower than without the reflector. Therefore, after the installation of the reflector in front of the ion gun, the ions extracted from the ion gun were almost neutralized by the reflector. The estimated percentage of neutralization was approximately 99.7%. The increase of ion current density without the reflector at higher RF power and acceleration voltage appears to be from the increase of ions in the ion gun chamber by increased plasma density and from the increase of ion extraction efficiency without scattering at the ion gun grids, respectively. The increase of ion current density with the reflector is also from the increased number of ions survived after the reflection without neutralization due to the increased ion flux incident on the reflector at higher RF power and higher acceleration voltage.

The ion species and their fluxes extracted from the ion gun without the reflector were measured using a quadrupole mass spectrometer that can measure the mass and energy of the ion. The mass spectrometer was located approximately 48 cm apart from the ion gun and was facing the ion gun directly. Fig. 3a shows ion species and their fluxes measured without the reflector using 10 sccm SF_6 at 500 V of acceleration

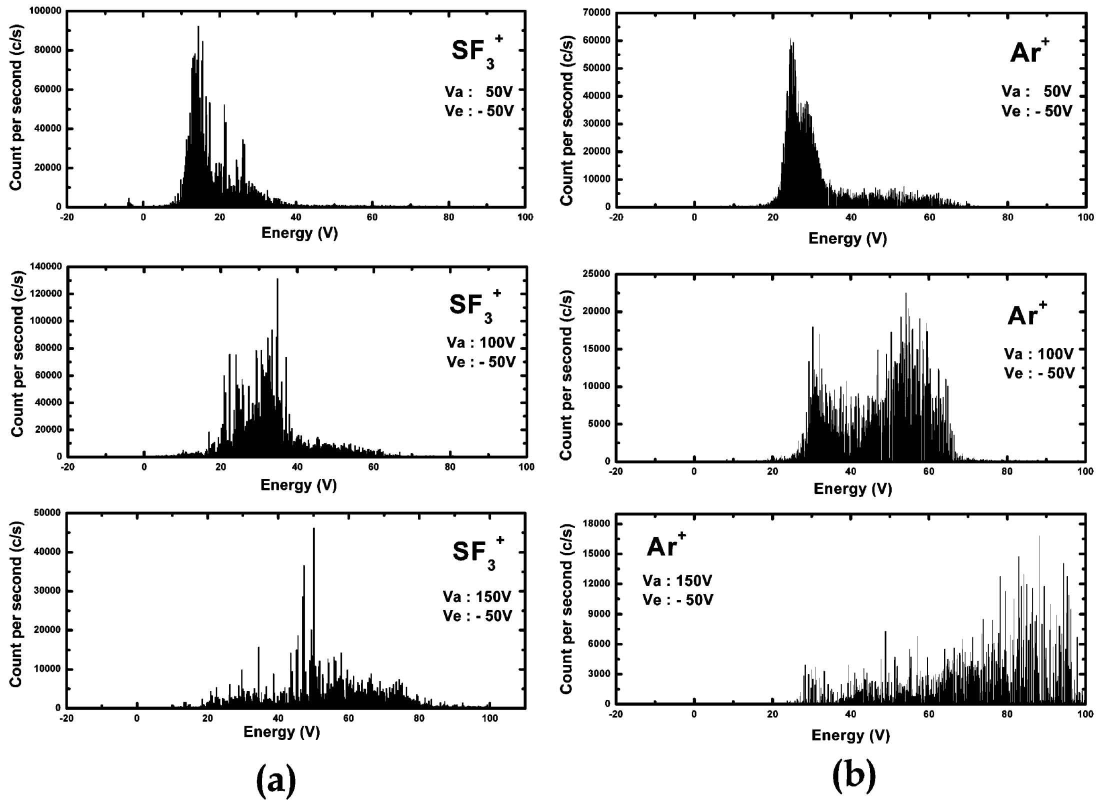
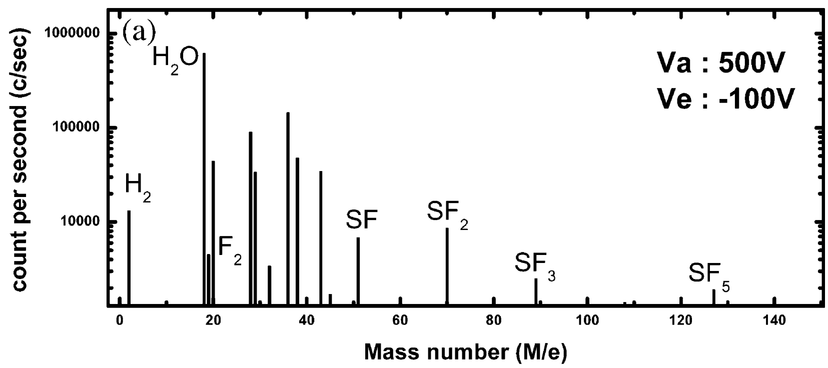


Fig. 4. Ion energy distribution of Ar^+ (a) and SF_3^+ (b) measured by the ion energy analyzer of the mass spectrometer without the reflector a function of acceleration voltage. (Extraction voltage, −100 V; SF_6 flow rate, 10 sccm.)

voltage, −100 V of extraction voltage, and 500 W of RF power. The mass spectrometer was negatively biased at −300 V to deflect any negative ions passing through the mass spectrometer and the ionizing filament was turned off to detect positive ions from the ion gun directly. In this figure, the positive ion species from SF_6 detected by the mass spectrometer were SF^+, SF_2^+, SF_3^+ and SF_5^+. The change in the flux of these positive ion species with the acceleration voltage is shown in Fig. 3b. The same conditions as Fig. 3a except for the acceleration voltage were also used. As shown in the figure, the increase of acceleration voltage generally increased the flux of SF_x^+ ions. The increase of SF_2^+ and SF_3^+ ions was significant with the increase of acceleration voltage and especially at the voltage higher than 300 V. The increase of ion current density with the increase of acceleration voltage in Fig. 2 appears to agree with the increase of SF_x^+ ion fluxes measured with increasing acceleration voltage even though the increase of SF_x^+ ion fluxes is insignificant at the voltage lower than 300 V. The inconsistency with the data on the ion current density at the voltage lower than 300 V is not fully understood. However, it might be related to scattering of the ions due to the distance of the ion gun and the mass spectrometer close to 10 times of the mean free path used in our experiment. (The distance between the Faraday cup and the ion gun was 5 cm.)

Ions extracted from the ion gun at a fixed energy can change the energy by the scattering during the travel through the vacuum chamber. Fig. 4a shows the energy distribution of SF_3^+ ion extracted from the ion gun measured using the mass spectrometer as a function of acceleration voltage from 50 to 150 V while the extraction voltage was kept at −50 V. As a reference, the ion energy distributions of Ar^+ ion for the same acceleration voltages were investigated and are shown in Fig. 4b. The gas flow rate of SF_6 and Ar was kept at 10 sccm. As shown in the figure, the energy distributions of SF_3^+ and Ar^+ were similar to each other with increasing acceleration voltage. The increase of acceleration voltage increased average energies of the SF_3^+ ion and Ar^+ ion. However, the energies of the ions are generally lower than the acceleration voltage. The average energy of the ions was approximately 1/2 of acceleration voltage for Ar^+ ion and approximately 1/3 for SF_3^+ ion. The differences of the average energy for different ions might be related to the differences in the mean free path.

The extracted reactive ions such as SF^+, SF_2^+, SF_3^+ and SF_5^+ at the ion gun are neutralized when the reflector



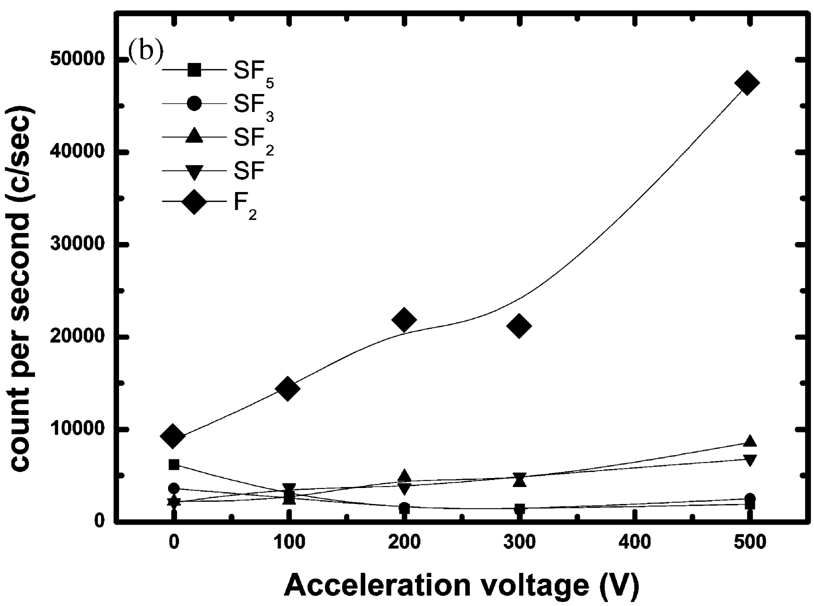


Fig. 5. (a) Neutral mass spectrum of the species with the reflector for 500 V of the acceleration voltage. (b) Neutral species measured by a quadrupole mass spectrometer with the reflector as a function of acceleration voltage. (Extraction voltage, −100 V; SF_6 flow rate, 10 sccm.)

is installed in front of the ion gun. The neutral species were measured by the mass spectrometer with the ionizer of the mass spectrometer turned on. With the reflector, due to the neutralization of almost all the ions extracted from the ion gun, nearly no signals from the ion gun were detected without turning on the ionizer. When the ionizer was turned on, the signals from neutral species were detected. Fig. 5a shows SF_x neutral species observed by the mass spectrometer from the ion gun with the reflector installed. The ion gun was operated at 500 V of acceleration voltage, −100 V of extraction voltage, and 10 sccm of SF_6 flow rate. As shown in the figure, radical peaks such as F_2, SF, SF_2, SF_3 and SF_5 were observed. When the ionizer is turned on, radicals arriving at the mass spectrometer are cracked, therefore, the peaks shown in Fig. 5a may not show the real neutral species arriving at the mass spectrometer. However, when SF_6 cracking pattern was investigated at the same ionizer voltage by flowing SF_6 neutral gas, only SF_5 signal was detected. Therefore, the signals shown in Fig. 5a should be related to the radicals arriving at the mass spectrometer. The difference in the detected species for the cases with and without the reflector was F_2. Only the case with the reflector showed the peak related to F_2. Fig. 5b shows the effect of acceleration voltage of the ion gun on the radical species detected at the mass spectrometer for the case with the reflector. The operation condition was the same as the case in Fig. 5a. As shown in the figure, the increase of acceleration voltage decreased radicals with higher mass such as SF_5 and SF_3, however, the radicals with lower mass such as SF_2, SF and F_2 were increased. The decrease of high mass peaks and the increase of low mass peaks with the increase of acceleration voltage appear to be from the increase of cracking of the high mass ions during the reflection at the reflector. The detection of F_2 that was not observed for the case without the reflector is also believed to be from the cracking of high mass SF_x^+ ions into low mass SF_x radicals and F_2. The increase of F_2 with the increase of acceleration voltage was significant and the etching by the low-angle forward-reflected neutral beam system used in the experiment using SF_6 gas appears to be controlled by the concentration of F_2. When SiO_2 was etched using this system with SF_6 gas, the etch rate of 22 nm/min with a vertical etch profile could be obtained with nearly no chargeup damage.

4. Conclusions

Neutral beam was formed using the low-angle forward reflection of the ion beam. Its degree of neutralization and its species were investigated as a function of acceleration voltage and RF power of the ion gun for SF_6 using a Faraday cup and a quadrupole mass spectrometer.

The ion current density from the ion gun measured using SF_6 increased with increasing RF power and acceleration voltage of the ion gun for both with and without the reflector. However, the ion current density decreased to 99.7% with the reflector, therefore, most of the ions were neutralized after the reflection at the reflector. When the ion species were measured using the mass spectrometer without the reflector, SF^+, SF_2^+, SF_3^+ and SF_5^+ were detected as the ions formed by SF_6 and the increase of acceleration voltage to the ion gun increased the flux and energy of these ions in general. However, in the case of the ion gun with the reflector installed, neutrals instead of ions were detected and the detected species were F_2, SF, SF_2, SF_3 and SF_5. The increase of acceleration voltage to the ion gun increased the lower mass peaks such as SF_2, SF and F_2 and decreased the higher mass peaks such as SF_3 and SF_5 suggesting the formation of lower mass neutrals at the reflector by the cracking and neutralization of the higher mass ions such as SF_3^+ and SF_5^+. The formation of F_2 was significant with the increase of the acceleration voltage. The etching by the low-angle forward-reflected neutral beam system used in the experiment using SF_6 gas appears to be controlled by the concentration of F_2.

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References

[1] T. Yunogami, K. Yokogawa, T. Mizutani, J. Vac. Sci. Technol. A 13 (3) (1995) 952.
[2] M.J. Goeckner, T.K. Bennett, J.Y. Park, Z. Wang, S.A. Cohen, International Symposium on Plasma Process-Induced Damage, (1997) 175.
[3] J. Yamamoto, T. Kawasaki, H. Sakaue, S. Shingubara, Y. Horiike, Thin Solid Films 225 (1993) 124.
[4] K. Yokogawa, T. Yunogami, T. Mizutani, Jpn. J. Appl. Phys. 35 (1996) 1902.
[5] S.R. Leone, J. Appl. Phys. 34 (1995) 2073.
[6] A. Szabo, T. Engel, J. Vac. Sci. Technol. A 12 (1994) 648.
[7] C.F. Abrams, D.B. Graves, J. Vac. Sci. Technol. A 16 (5) (1998) 3006.
[8] B.A. Helmer, D.B. Graves, J. Vac. Sci. Technol. A 16 (6) (1998) 3502.
[9] U. Thumm, J. Ducree, P. Kurpick, U. Wille, Nucl. Instr. Meth. B 157 (1999) 11.
[10] D.H. Lee, J.W. Bae, S.D. Park, G.Y. Yeom, Thin Solid Films 398 (2001) 647.
[11] M.J. Chung, D.H. Lee, G.Y. Yeom, Thin Solid Films 420–421 (2002) 579.