Study of the charge transport mechanism in pulsed laser deposited AlN:Si films

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Abstract. AlN films doped with Si (AlN:Si) were synthesized on p-Si(100) substrates by pulsed laser deposition. Al-AlN:Si-Si metal-insulator-silicon (MIS) structures were formed and their current-voltage characteristics measured at 77 K and 290 K were analyzed. The results revealed that the charge transport is carried through the AlN:Si-Si MIS structures by the mechanism of trap space charge limited current.

1. Introduction

Aluminum nitride has wide application prospects in the area of high-power, high-temperature electronic and UV optoelectronic devices, especially for UV solid-state LED and lasers. For these applications, it is indispensable to prepare AlN films and structures with good and controllable n- and p-type conduction. AlN is a semiconductor with the wide energy gap of 6.2 eV. Because of this, AlN doping is a complex process. To obtain n-type AlN, Si doping is widely used [1,2]. During the Si doping, compensation of Si donors occurs, as it has been observed in MBE deposited AlN films [1]. Deep levels introduced in MBE deposited AlN films create a high-resistivity state in the films irrespectively of the Si doping [2]. Therefore, studying the electrical conductivity of Si doped AlN films prepared by different methods is essential for prospective applications of such AlN semiconductor structures.

Pulsed laser deposition (PLD), because of its capability of reproducing the target stoichiometry in the deposited films, is suitable for preparation of AlN:Si films with controllable Si doping level. Establishing the charge-transport mechanism in PLD AlN:Si films is an unavoidable step in achieving reliable and effective Si doping of AlN. Measuring the current-voltage (I-V) characteristics at different temperatures, which reveals, in particular, the deep levels role in the charge transport through the deposited films, is a powerful technique for studying the electro-physical properties of semiconductor structures.

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In this paper we present results on the study of the charge transport mechanism in pulsed laser deposited AlN films doped with Si. For this purpose, metal-insulator-silicon (MIS) structures with PLD AlN:Si films were prepared and their DC $I$-$V$ characteristics were recorded. The charge transport mechanism was established by analyzing these characteristics.

2. Experimental details
Si-doped AlN films were synthesized on $p$-type Si(100) substrates by pulsed laser deposition. The PLD targets were prepared by homogeneously mixing AlN and Si (10 at. %) powders, followed by pressing and sintering. The distance between the target and substrate was set at 5 cm. After loading the substrate and target, the chamber was evacuated to a residual pressure of $10^{-4}$ Pa and the substrate was heated up to 800 °C. During ablation, the target was rotated and translated along two orthogonal axes to avoid piercing and to improve the morphology of the films deposited. The deposition was performed in nitrogen at a dynamic pressure of 0.1 Pa or 10 Pa. AlN:Si films with ~200 nm thickness were deposited by applying 20 000 laser pulses generated by an UV KrF* laser source ($\lambda = 248$ nm, $\tau_{\text{FWHM}} = 25$ ns) operating at 10-Hz repetition rate and incident laser fluence of 10 J/cm$^2$ on the target.

For the electrical measurements, MIS capacitors with PLD AlN:Si films were formed by vacuum evaporation through a metal mask of Al dots on the AlN surface and a continuous Al film on the Si wafer backside. The $I$-$V$ characteristics were measured at 290 K and 77 K. The measurement sequence began from 0 V toward the negative or positive voltages applied to the Al-dot contact on the film surface followed by a voltage reversal toward zero applied bias voltage. For clarity, we denote below the initial voltage passage from zero to minimal negative or maximal positive voltage as “up”, and the voltage passage going back to zero as “down” directions.

Our earlier investigations on PLD AlN films have revealed that the their structure is strongly dependent on the deposition conditions and, in particular, on the nitrogen pressure [3,4]. Therefore, it was expected that the AlN:Si films would also exhibit different structures and, thus, different electrical properties. Taking this into consideration, the AlN:Si films were examined by a large-angle (2$\Theta = 0–90^\circ$) X-ray Philips X’Pert diffractometer with Cu radiation ($\lambda = 0.154056$ nm).

3. Results and discussion
Figure 1 presents the recorded XRD patterns of the films studied. The appearance of Bragg peaks related to a crystalline phase and identified using the ASTM data basis [5] is evidence of the presence of crystallites in the mainly amorphous matrix growing in a cubic phase predominantly in the (111) crystallographic direction. The broadening of the peaks observed as compared with the diffraction Bragg peak of a perfect crystal revealed that the randomly oriented crystallites had grown up to sizes in the nanoscale range. The films deposited at 0.1 Pa N$_2$ pressure had a higher degree of crystallization.

Figure 2 presents the $I$-$V$ characteristics of a MIS capacitor with an AlN:Si film deposited at 10 Pa. As is evident, no hysteresis is observed at electric fields up to $4.5 \times 10^4$ V cm$^{-1}$. Under these electric fields, the current is proportional to the applied voltage and the $I$-$V$ curves recorded with positive (forward direction) or negative (reverse direction) voltages, applied to Al-dot contacts, are with equal or slightly different slopes (inset in figure 2). The slope of the curves corresponds to a specific resistivity of $1.0 \times 10^4 \, \Omega$ cm of the AlN:Si film deposited at the given conditions.

In the case of MIS capacitors with an AlN:Si film deposited at 0.1 Pa, the $I$-$V$ characteristics are non-ohmic and a hysteresis effect appears (figure 3). In both reverse and forward directions, the current is different in an up-and-down cycle. During the initial voltage passage from zero to minimal negative or maximal positive voltage (up), the current density is smaller than that obtained by going back...
to zero voltage (down). This means that during the first stage, the charge carriers are captured by traps in the AlN:Si films. In the forward direction, when the electrical field exceeded $1.2 \times 10^5$ V/cm the current became unstable. Keeping constant the voltage at ~2.5 V for several minutes, the current increased approximately twice. Because of this, in the forward direction the hysteresis effect was much stronger.

The specific resistivity in forward direction at the lower electrical fields of $5.4 \times 10^3$ V/cm (up) and $4.2 \times 10^3$ V/cm (down) (figure 3) was equal to $6.6 \times 10^5 \, \Omega \cdot \text{cm}$ and $9.6 \times 10^4 \, \Omega \cdot \text{cm}$, respectively. Correspondingly, in reverse direction at the lower electrical fields of $1.0 \times 10^4$ V/cm (up) and $4.2 \times 10^3$ V/cm (down) its value was $5.1 \times 10^5$ and $2.4 \times 10^5 \, \Omega \cdot \text{cm}$, respectively. At the higher electrical fields of $1.2 \times 10^5$ V/cm, the resistivity decreased in both directions and was in the range of $(9 \times 10^4 \div 2.4 \times 10^5) \, \Omega \cdot \text{cm}$.

The I-V characteristics for the 0.1 Pa case (figure 3) were further analyzed by replotting them as ln$J$ versus ln$V$ plots (not shown here). The slope of the plots (excluding the first three points near zero applied voltage) indicates that the current density $J$ is proportional to $V^\xi$. In the initial voltage passages (up) in forward direction the value of this $\xi$ parameter is equal to $\xi = 1.97$, while in reverse direction $\xi = 2.02$. In the return passages (down), the $\xi$ values are $\xi = 1.59$ and $\xi = 1.60$ for reverse and forward bias, respectively. As it is established in [6], a $I(\xi)$ dependence with $\xi = 2$ is evidence that the current in the insulating film is space-charge limited and occurs via single deep levels with equal position in the insulator energy bandgap. In such a case, both the density of trapped charges and their effective velocity are proportional to the applied voltage $V$ and, therefore, the current is proportional to $V^2$. For the AlN:Si MIS structures, it is the case when the current is measured in the initial voltage passages (up). For the return voltage passages (down), the observed deviation of $\xi$ from 2 ($\xi < 2$) is connected with charge trapping at deep levels having long relaxation times.

In AlN, the electron mobility exceeds largely the hole mobility. For example, at 300 K in a pure AlN film, the electron mobility is $800 \, \text{cm}^2 \, \text{V}^{-1} \, \text{sec}^{-1}$ [6], while in a Mg doped AlN film, the hole mobility is $(10 \div 26) \, \text{cm}^2 \, \text{V}^{-1} \, \text{sec}^{-1}$ [7]. In our case, the current through the MIS structures with AlN:Si film deposited at 0.1 Pa is only 2-3 times as high in forward direction as that in reverse direction, while the difference between the forward and reverse currents through the MIS structures with 10 Pa AlN:Si film is even smaller (2–3 %). Therefore, in both cases the current is carried by electrons.

The above considerations allow us to infer that the electrical current though the AlN:Si films investigated is carried by electrons via deep levels with single energy level; in other words, the current through the AlN:Si films is the so-called space charge limited current.

Typical I-V curves of AlN:Si MIS structures measured at 77 K and 290 K and in the initial voltage passages are shown in figure 4. It is evident that in both reverse and forward directions the current density at 290 K is slightly higher than that at 77 K. At low electric fields, the I-V curves are linear for
both temperatures, while for the AlN:Si film deposited at 10 Pa the linear part extends over a larger range of voltages. The specific resistivity $\rho$ of the AlN:Si films is determined from the slope of the linear part of the curves and the results are summarized in table 1.

The temperature behavior observed of the current through the AlN:Si MIS structures is consistent with charge transport by electron hopping from occupied deep levels to non-occupied ones. It is known that in AlN the defects related to Al vacancies are with acceptor properties [8] and, therefore, the Si donors are partly compensated in the AlN:Si film by Al-vacancy acceptors. Such a process considerably reduces the efficiency of AlN doping with Si donors with the purpose of obtaining $n$-type conduction. Further investigations are needed to distinguish between the mechanisms of electron variable-range hopping and electron hopping to nearest non-occupied acceptor in these AlN:Si films.

![Figure 4. I-V characteristics measured at 290 K (full symbols) and 77 K (empty symbols) of MIS capacitors with AlN:Si film deposited at a nitrogen pressure of 0.1 Pa (a) and 10 Pa (b).](image)

**Table 1.** Specific resistivity $\rho$ of AlN:Si films deposited at different nitrogen pressures.

| Nitrogen pressure | 0.1 Pa | 10 Pa |
|-------------------|--------|-------|
|                   | $\rho$ (77 K) $[\Omega \text{ cm}]$ | $\rho$ (290 K) $[\Omega \text{ cm}]$ | $\rho$ (77 K) $[\Omega \text{ cm}]$ | $\rho$ (290 K) $[\Omega \text{ cm}]$ |
| **Reverse I-V**    | $1.56 \times 10^4$ | $6.22 \times 10^3$ | $1.29 \times 10^5$ | $4.38 \times 10^4$ |
| **Forward I-V**    | $1.18 \times 10^4$ | $6.22 \times 10^3$ | $6.52 \times 10^3$ | $4.60 \times 10^4$ |

**Conclusions**

We established that the electrical current through PLD AlN:Si films synthesized at the conditions described is carried by electrons via deep levels in the AlN:Si energy bandgap. The trap space charge limited current occurs by electron hopping from occupied deep acceptor levels to non-occupied ones.

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