Study of the charge transport mechanism in AlN:Cr films synthesized by pulsed laser deposition

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Abstract. Thin films of AlN doped with Cr were formed on p-Si(100) substrates by pulsed laser deposition. Al-AlN:Cr-Si MIS structures were formed and their current–voltage and 1 MHz admittance characteristics were measured. The considerably smaller increase of the conductance at 300 K in comparison to that measured at 77 K is an evidence for tunneling type of conductance in these MIS structures. The current is limited by space charge at deep levels (traps) in these AlN:Cr films which determines the mechanism of the charge transport through the MIS structures. The density of the filled electron traps is in the order of $10^{16}$ cm$^{-3}$.

1. Introduction
The possibility for applying diluted magnetic semiconductors (DMS) in spintronics devices and structures has led to the preparation and investigation of different DMS thin films. DMS is formed when metal ions are replaced by magnetic ions of transition metals such as Co, Cr or Mn. Ferromagnetism with Curie temperatures as high as 900°C is observed in Cr-doped AlN (denoted further as AlN:Cr) films [1]. For preparation of these films, the incorporation of Cr ions is accomplished usually by Cr co-evaporation during AlN MBE deposition [2] or by Cr ion implantation into already deposited AlN film [3], or by reactive dc co-sputtering of Al and Cr in a nitrogen gas ambient [4]. The pulsed laser deposition (PLD) technique, due to its capability of reproducing the target stoichiometry in the deposited film, is very suitable for preparation of AlN:Cr films. Prospective AlN:Cr devices and structures formed on Si substrates will be compatible with devices and integrated circuits in contemporary Si planar technology. For spintronics applications, such as resonant tunneling diodes and tunneling magnetoresistance structures, knowledge of the charge transport mechanism in these films is of great importance.

Our research interest was recently focused on AlN thin films doped with Cr, as we have used pulsed laser deposition for film preparation. Some studies of the structural and optical properties of PLD AlN:Cr films have already performed [5]. In this paper we present results of the study of the charge transport mechanism in the PLD AlN:Cr films. For this purpose, MIS structures with PLD AlN...
films were formed and their DC current-voltage (I-V) and admittance (capacitance and conductance) characteristics were measured. Through an analysis of the I-V characteristics, the capacitance–voltage (C-V) and conductance–voltage (G-V) characteristics obtained, the charge transport mechanism was established.

2. Experimental details
Thin AlN films doped with Cr were synthesized on single crystalline Si(100) p-type substrates by pulsed laser deposition. The PLD targets were prepared by homogeneously mixing AlN and Cr (10 at.%) powders followed by pressing and sintering. The films were grown using a KrF* ($\lambda = 248$ nm) excimer laser generating pulses of $\tau_{FWHM} \leq 25$ ns at a repetition rate of 10 Hz. During ablation, the target was rotated and translated along 2 orthogonal axes to avoid piercing and improve the morphology of the deposited films. The laser beam was incident at 45°, while the ablation plasma flume was evolving normally to the target surface. The target - substrate distance was 5 cm. After loading the substrate and target, the deposition chamber was pumped down to a residual pressure of $5.0 \times 10^{-4}$ Pa. Before deposition, the substrate was heated up to 800°C for 1 hour for the purpose of decomposing native SiO$_2$ on the Si surface. The substrate temperature was kept at 800 °C during deposition, providing conditions for crystalline growth of AlN. The laser fluence on target was 10 J/cm$^2$. Deposition of one film necessitated 15 000 consecutive laser pulses yielding a $\sim 300$ nm thick film. The film synthesis was undertaken in vacuum at a residual gas pressure of $10^{-3}$ Pa.

To perform electrical measurements, metal–Al N:Cr–silicon capacitors were formed by vacuum evaporation of Al dots with 0.5 mm diameter on the film surface and a continuous Al film on the Si wafer backside. Capacitance–voltage (C-V) and conductance–voltage (G-V) measurements were carried out by using a digital LCR meter E7-12 at room temperature and at 77 K at test voltage frequency of 1 MHz. The DC current–voltage (I-V) characteristics were measured only at room temperature.

3. Results and discussion
Applying the bias voltage to the AlN:Cr-Si structure during the I-V measurements changed the current by several percents. Because of this, we increased the bias voltage from zero to its maximal value at a constant step for a total time of $\sim 30$ min. The maximal voltage was kept constant for $\sim 15$ min before starting the decrease of the voltage at the same step. The common feature of these characteristics was their hysteresis. The current value measured depended strongly on the measurement sequence and sweep direction. Figure 1 presents the I-V curves recorded with a measurement sequence starting from 0 V toward negative or positive voltages applied to the contact on the AlN:Cr film surface followed by a decrease of the absolute value of the voltage applied toward zero bias.

It has been established that the electron mobility exceeds the hole mobility in AlN by several factors, for example, at 300 K the electron mobility in pure AlN is 800 cm$^2$V$^{-1}$sec$^{-1}$ [6], while the hole mobility in Mg doped AlN is (10÷26) cm$^2$V$^{-1}$sec$^{-1}$ [7]. Since in the “forward” direction, i.e. under accumulation, the current density is only about 30-50% larger than that measured in the “reverse” direction, i.e. in inversion (figure 1), it can be concluded that in our PLD AlN:Cr films in both directions the DC current is carried out by electrons. As it is seen, in both sweep directions at a given voltage the current measured when the electric field is increased is larger than that measured with decreasing electric field. Such a current hysteresis is an indisputable evidence that during electron passage through the AlN:Cr film some of electrons are captured by empty deep levels (traps) in these films. These...
captured electrons oppose the current flow leading to lower current density in the directions of decreasing electrical fields. In the case of uniform trap concentration in the film, the density of these filled electron traps, \( N_t \), can be estimated from the electrical field change \( \Delta V/\Delta d_{AlN} = q N_t d_{AlN}/\varepsilon_{AlN} \), where \( d_{AlN} \) is the thickness of the film and \( \varepsilon_{AlN} \) is its permittivity. To restore the same current density, as is evident from figure 1, the electrical field applied should be changed by \( \Delta V_j/\Delta d_{AlN} \), where \( \Delta V_j \) is the voltage difference between the up and down plots at a given current density. With \( \Delta V_j = 0.39 \) V at \( J = 3 \) A/cm\(^2\) (forward direction, figure 1) and \( \varepsilon_{AlN} \approx 30 \varepsilon_0 \) (determined from the C-V characteristics), the density estimated of filled electron traps is \( N_t = 7.2 \times 10^{15} \) cm\(^{-3}\). Since the permittivity of AlN is frequency dependent [8], \( \varepsilon_{AlN} \) value at low frequencies is greater than that measured at 1 MHz and, therefore, the real value of \( N_t \) is greater than its estimated value. A trap density of \( \sim 10^{16} \) cm\(^{-3}\) is reasonable for an insulator film which, together with the hysteresis observed in the I-V curves, indicate that the current in the AlN:Cr films is limited by space charge. As it is shown in [9], in that case the current is determined by the density of the charge trapped in the film deposited and the effective velocity of the charge carriers. As both density and velocity are proportional to the applied voltage, the experimentally measured current is proportional to \( V^\xi \), where \( \xi = 2 \) for traps with a single energy level or close to it for traps with normal energy distribution around a fixed energy position. In [9] it has been also established that the trap space-charge limited current at lower electrical fields should be ohmic. This is in good agreement with our observations that the I–V dependence (figure 1) is linear at low electrical fields applied (below \( 10^3 \) V cm\(^{-1}\)) and obeys the \( J \approx V^2 \) dependence at higher electrical fields as the current increases rapidly and becomes proportional to \( V^2 \).

The dielectric properties of an insulating film are usually characterized by its resistivity value \( \rho = \rho_{AlN}/A \), where \( \rho \) is the specific resistivity of the material and \( A \) is the contact area. In general, \( \rho \) has a constant value. However, as it is evident from the I–V characteristics in figure 1, in our case the specific resistivity \( \rho \) depends on the electric field applied due to the trapped-charge influence on the electrical conduction in the PLD AlN:Cr films. The \( \rho(V) \) dependence obtained is given in figure 2.

The C-V and G-V characteristics of the MIS structures are shown in figures 3 and 4, respectively. Keeping the same voltage sweep directions, the plots remain identical during several records. The same situation occurs even when the voltage sweep rate is decreased by a factor of ten. At both temperatures, the accumulation, depletion and strong inversion regions are clearly discernable. The permittivity \( \varepsilon_{AlN} \) of the AlN film, calculated from the capacitance value in accumulation, is equal to \( 30.6 \varepsilon_0 \) at 300 K and to \( 25 \varepsilon_0 \) at 77 K. These values are higher than the value \( \varepsilon_{AlN} \approx 10 \varepsilon_0 \) estimated from the optical measurement, as reported in [10]. Such high values of \( \varepsilon_{AlN} \) have been related to the nitrogen vacancies contribution to capacitance of the AlN [11]. Another evidence for defects in these AlN-Si structures is the extended depletion region between the accumulation and deep inversion regions.

In the C-V plots (figure 3), a maximum near zero bias voltage is observed at both temperatures. Such a capacitance feature is observed in many semiconductor structures and is connected with the back-to-back Schottky model of depletion regions on both sides of the grain boundary [12]. The change of the widths of these layers when voltage is applied causes the capacitance maximum observed near zero bias voltage. The capacitance saturation in accumulation indicates that the trapped charge concentration at defects in the AlN:Cr films does not depend on the bias voltage applied. This is evidence of the fact that all traps are filled with charge carriers during the measurements.

![Figure 2](image-url)
Similarly to the capacitance, the conductance (figure 4) also saturates in accumulation and deep inversion regions due to the complete filling of traps in the AlN:Cr films at these bias voltages. In the regions where the capacitance and conductance are constant, i.e. below $-8$ and above $8$ V, all deep levels lying below the charge carrier quasi-Fermi level in the AlN:Cr film are filled up. At 300 K, the value of the conductance saturation in accumulation is approximately twice as high as that at 77 K, while its value in deep inversion is 50 % higher than that at 77 K. These observations are an indication for tunneling-type conductance in the AlN:Cr-Si MIS structures investigated.

4. Conclusions
It was established that deep levels in the PLD AlN:Cr films contribute to the capacitance and conductance of MIS structures formed with AlN:Cr films. At electrical fields higher than $10^3$ Vcm$^{-1}$ the conductance is almost constant, which is caused by a complete filling of deep levels below the quasi-Fermi level in the AlN:Cr film. The trapped charge carriers at deep levels influence the current density which leads to a hysteresis in the C-V and I-V characteristics and to a dependence of the specific resistivity on the electrical field applied. Due to the high concentration of deep levels ($N_t \sim 10^{16}\text{cm}^{-3}$) in the PLD AlN:Cr films, the charge transport mechanism is trap-space-charge-limited current.

Acknowledgements
The authors acknowledge the support of this work under the Collaboration Agreement between the Bulgarian and Romanian Academies of Sciences for 2007–2009.

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