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Charging effect on current conduction in aluminum nitride thin films containing Al nanocrystals

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The presence of Al nanocrystals (nc-Al) in AlN thin films is found to enhance the current conduction of the thin film system greatly due to the formation of tunneling paths of nc-Al arrays, and the nc-Al/AlN system shows a quasi-two-dimensional transport following a power law. However, charge trapping in nc-Al reduces the current conduction because of the increase in the tunneling resistance and/or the breaking of some tunneling paths due to Coulomb blockade effect. The current conduction also evolves with a trend towards one-dimensional transport due to the breaking of some transverse tunneling paths as a result of the charge trapping. *© 2006 American Institute of Physics*.
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There has been an increasing interest in aluminum nitride (AlN) thin film as it is a promising material for applications in surface acoustic wave devices and light-emission devices.[1–6] In addition, with its high thermal conductivity,[7] reasonable thermal match to semiconductors (such as Si, GaAs, and GaN) and small lattice mismatch,[7,8] and wide band gap (6.2 eV),[6] AlN thin film could be used as a gate dielectric for field-effect transistors.[9,10] Recently, it is also found that an AlN thin film embedded with Al nanocrystals (nc-Al) exhibits a memory effect which can be used for non-volatile memory devices.[11] The memory effect is actually a result of charging and discharging in the nc-Al. On the other hand, although AlN has a low conductivity due to its wide band gap, the distribution of nc-Al in AlN matrix could affect the current conduction in AlN. In the present study, we have examined the current transport of AlN thin films embedded with nc-Al and the influence of charging in the nc-Al on the current transport. It is observed that the presence of the nc-Al in the AlN matrix can enhance the current conduction greatly and the current-voltage (I-V) characteristic follows a power law showing a quasi-two-dimensional transport. However, the charging in the nc-Al reduces the current conduction, and the system evolves with a trend towards one-dimensional transport as a result of the charging effect. The phenomena can be explained by a model of charge transport in nc-Al arrays.

Al-rich AlN film of 50 nm in thickness was deposited on n-type, (100)-oriented Si wafers. The deposition was carried out by rf magnetron sputtering of a pure Al target in a gas mixture of argon and nitrogen. The flow rate ratio of Ar to N_2 is maintained at 1:5. A 200 nm aluminum layer was then deposited to form the gate electrode. The wafer back side was coated with a layer of aluminum of about 500 nm in thickness after removing the initial oxide. An alloying process was conducted at 425 °C in N_2 ambient to form Ohmic contacts. X-ray photoemission spectroscopy (XPS) analysis was performed using a Kratos AXIS spectrometer with monochromatic Al $K\alpha$ (1486.71 eV) x-ray radiation. The XPS result shows that the as-fabricated films are Al rich. The details have been reported in our previous work.[11] The high resolution transmission electron microscopy (HRTEM) image shows the existence of nc-Al embedded in the AlN matrix, as shown in Fig. 1. The concentration of nc-Al was evaluated with HRTEM images to be in the order of $1 \times 10^{11}/\mathrm{cm}^2$. The I-V measurement and the experiment of charging/discharging the nc-Al were carried out with a Keithley 4200 semiconductor characterization system at room temperature. The capacitance-voltage (C-V) measurement

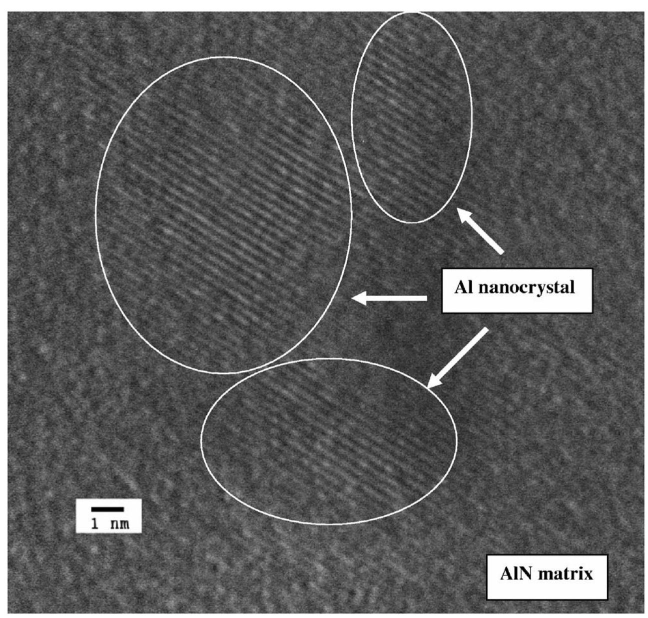

FIG. 1. HRTEM image of nc-Al embedded in AlN matrix.

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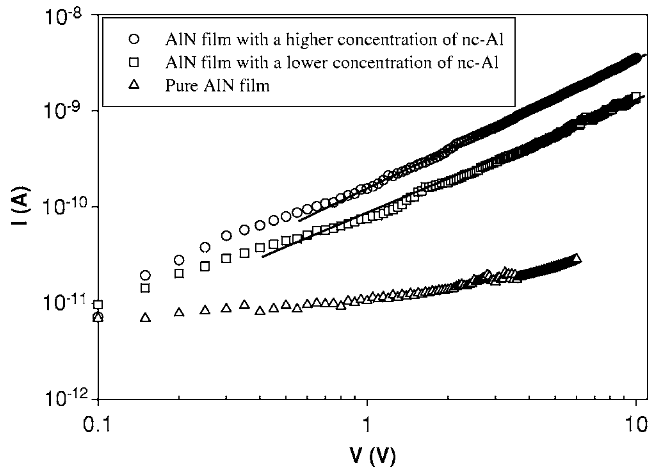

FIG. 2. *I-V* characteristics of AlN thin films without and with nc-Al. For the sample with a lower concentration of nc-Al, the ratio of Al:N is 1.6:1, and for the sample with a higher concentration of nc-Al, the ratio of Al:N is 3:1.

was performed with an HP4284 *LCR* meter.

Figure 2 shows a comparison of *I-V* characteristic between a pure AlN thin film and AlN thin films with identical thickness containing the nc-Al. The presence of nc-Al greatly enhances the current conduction. The conduction enhancement by the nc-Al can be explained by Fig. 3(a). Electron tunneling can take place between adjacent uncharged nanocrystals, and many such nanocrystals form conduction paths connecting the Si substrate to the metal gate as shown in Fig. 3(a). With the existence of many tunneling paths formed by the nc-Al, the current conduction of the thin film system is drastically enhanced. As can be seen in Fig. 2, the current conduction is increased with nc-Al concentration, which can be attributed to the formation of more tunneling paths.

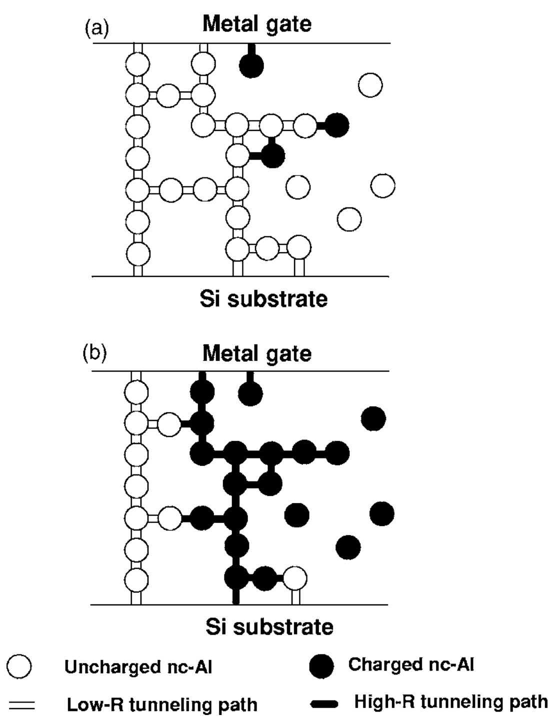

FIG. 3. (a) Schematic illustration of the formation of tunneling paths between adjacent uncharged nc-Al embedded in the AlN matrix and (b) illustration of the influence of charge trapping in some nc-Al on the tunneling paths.

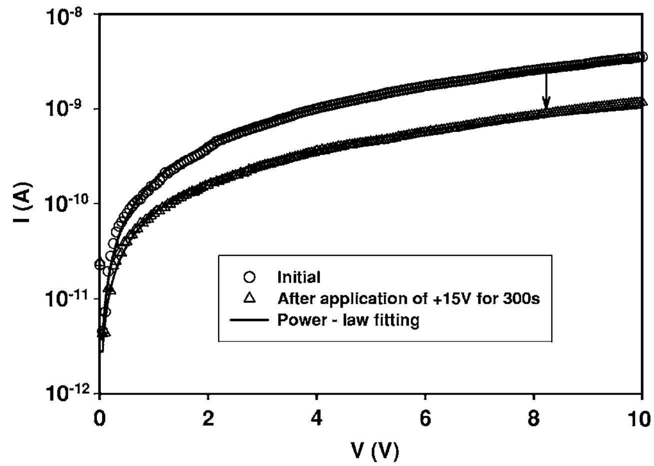

FIG. 4. *I-V* characteristics before and after application of +15 V for 300 s. The lines show the fittings based on Eq. (1). $I_0=2.40\times10^{-8}$ A and $\zeta=1.28$ before application of the voltage and $I_0=9.24\times10^{-10}$ A and $\zeta=1.12$ after application of the voltage.

Another important observation from Fig. 2 is the linear relationship between log(I) and log(V) (i.e., a power-law relationship between I and V) for the AlN thin film containing nc-Al. The power-law behavior could be explained by a model similar to the one of collective charge transport in arrays of normal-metal quantum dots (QDs).[12] The current through an array of metallic QDs separated by tunnel barriers is shown to follow the power-law relationship[12,13]

$$I = I_0 (V - V_{\mathrm{th}})^{\zeta}, \tag{1}$$

where ζ is the scaling exponent and V_{th} is the threshold voltage. The scaling exponent $\zeta=1$ and 5/3 for the one- and two-dimensional arrays of QDs, respectively.[12,13] Equation (1) can be used to fit our experimental result of the system of nc-Al embedded in AlN matrix, and the fitting can yield the values of the factors including ζ, V_{th}, and I_0 of Eq. (1). Figure 4 shows such a fitting to the *I-V* characteristics before and after the application of +15 V for 300 s. ζ is found to be in the range of 1.1–1.3, depending on prior application of a voltage. This indicates that the current conduction of the system is a quasi-two-dimensional transport (i.e., in between one- and two-dimensional transports). The situation could be

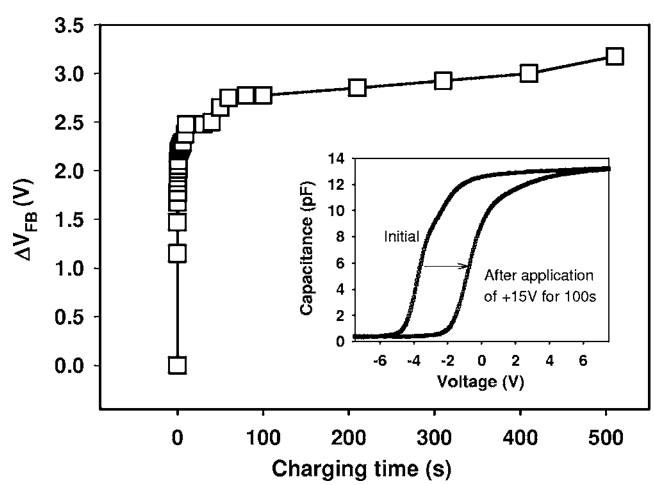

FIG. 5. Flatband voltage shift (ΔV_{FB}) as a function of charging time. The inset shows an example of *C-V* characteristics before and after the application of voltage.

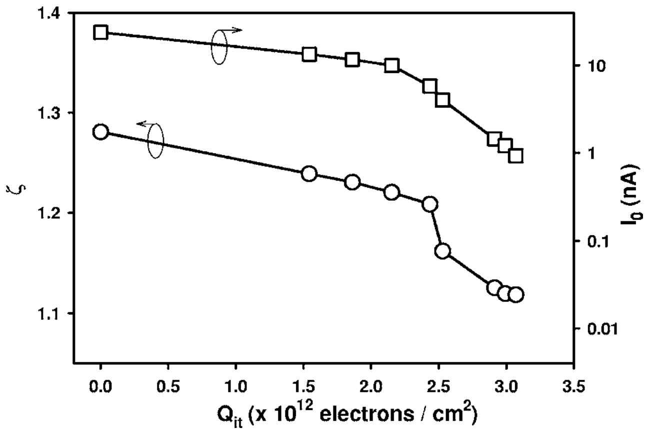

FIG. 6. I_0 and ζ as a function of Q_{it}.

like that there are two-dimensional tunneling paths in addition to one-dimensional tunneling paths as shown in Fig. 3(a). The threshold voltage is found to be approximately zero at room temperature. I_0 is observed to decrease after application of a voltage. For example, for the case shown in Fig. 4, I_0 decreases from the initial 2.4×10^{-8} to 9.2×10^{-10} A after the application of +15 V for 300 s.

As mentioned above, both ζ and I_0 depend on a prior application of voltage to the sample. Such dependence can be attributed to the charging in the nc-Al caused by the application of voltage, to be explained later. To confirm the charging in the nc-Al, *C-V* measurement is carried out to determine the flatband voltage shift, which depends on the charges trapped in the nc-Al. Figure 5 shows the flatband voltage shift (ΔV_{FB}) as a function of time (i.e., the charging time) under a bias of +15 V. The positive flatband voltage shift indicates electron trapping in the nc-Al. The electron trapping is due to the electron injection from the substrate under the influence of the positive gate bias. The electron trapping can be described with the equivalent areal trapped charge density (Q_{it}) at the AlN/Si interface calculated from ΔV_{FB}. Therefore, the charging time dependence of ΔV_{FB} shown in Fig. 5 can be easily translated into the charging time dependence of Q_{it}. To study the effect of charging in nc-Al on the current transport, electron trappings with different amounts in the nc-Al are achieved by varying the charging time under the constant bias of +15 V. For a given charging time, the Q_{it} is obtained from the flatband voltage shift based on the *C-V* measurement, and I_0 and ζ are obtained from the fitting to the *I-V* characteristics. In this way, we are able to examine the influence of electron trapping in the nc-Al on I_0 and ζ. Figure 6 shows I_0 and ζ as a function of Q_{it}.

As can be observed from Fig. 6, the charge trapping leads to a reduction in both I_0 and ζ. The reduction in I_0 is attributed to the increase of the tunneling resistance and/or the decrease in the number of tunneling paths as a result of the charge trapping. On the other hand, ζ decreases from 1.28 for $Q_{it}=0$ to 1.12 for $Q_{it}=3.1 \times 10^{12}$ e/cm^2, but it is still within the range between the upper limit ($\zeta=5/3$) for two-dimensional arrays and the lower limit ($\zeta=1$) for one-dimensional arrays. This indicates that the current conduction of the system is still a quasi-two-dimensional transport, but it evolves with a trend towards the one-dimensional transport when the charge trapping is increased. This evolution is due to the breaking of some transverse tunneling paths as a result of charge trapping in the nc-Al, as discussed below.

The scenario of the influence of charge trapping in nc-Al on the tunneling paths is shown in Fig. 3(b). Electron trapping in one nc-Al will affect the tunneling of other electrons into this nc-Al. The resistance (R) of the tunneling paths involving this nc-Al will increase due to the electrostatic interaction with the electrons trapped in the nc-Al. In addition, the tunneling paths could be broken due to the Coulomb blockade effect also. Therefore, as a result of the charging in nc-Al, I_0 will decrease because of the increase in the R and/or the decrease in the number of available tunneling paths due to the breaking of some tunneling paths. With the breaking of some transverse tunneling paths, the current conduction of the system will evolve towards the one-dimensional transport. On the other hand, if the nc-Al size is reduced, the Coulomb charging energy increases, and the Coulomb blockade is enhanced. In this case, the current conduction will be reduced, and most likely I_0 will decrease.

In conclusion, the presence of the nc-Al in the AlN matrix enhances the current conduction of the thin film system greatly due to the formation of many conductive tunneling paths of nc-Al. The *I-V* characteristic of the system follows a power law, i.e., $I=I_0(V-V_{th})^{\zeta}$, where the threshold voltage $V_{th} \approx 0$ and the factors I_0 and ζ are sensitive to the charge trapping in the nc-Al. As a result of the charging in nc-Al, I_0 decreases because of the increase in the resistance of the tunneling paths and/or the breaking of some tunneling paths due to Coulomb blockade effect. On the other hand, ζ also decreases with a trend towards $\zeta=1$ of one-dimensional arrays, showing that the current conduction evolves from a quasi-two-dimensional transport towards the one-dimensional transport due to the breaking of some transverse tunneling paths as a result of the charge trapping.

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