Memory Effects Induced by Space Charge Polarization in a SmNiO₃ Film

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Abstract:
This report presents the first characterization of a correlated oxide SmNiO₃ (SNO) used in electronic device structures. In a MOS capacitor with a gate insulator of a SNO film sandwiched between two SiO₂ layers, memory effects are observed. The response time of polarization is over a microsecond. This implies that space charge polarization is dominant. Due to the instability of Ni³⁺ valence state, oxygen vacancies appear to lead to a polarization effect. In a MOSFET, counterclockwise hysteresis is observed, which is consistent with polarization switching effect. The stored information decays gradually with the retention time of around ten seconds.

Summary of Research:
Rare-earth nickelates RNiO₃ (R stands for rare-earth elements such as Pr, Nd, and Sm) exhibit metal-insulator phase transition (MIT) as a function of temperature [1]. The MIT temperature increases with the size of the element [2]. At high temperature, the RNiO₃ compounds are metallic with orthorhombic symmetry. As temperature decreases, charge disproportionation occurs between Ni sites, reducing the symmetry to monoclinic and resulting in a transition to an insulating state [3]. SNO is of particular interest because it is the first nickelate with MIT temperature above room temperature. Owing to instability of 3+ oxidation state of Ni, oxygen vacancies are present in a SNO film [2]. They lead to space charge creation and influence the conduction properties of SNO thin films. Space charge can affect the dielectric property of a SNO film. In this work, the dielectric properties of SNO are examined and the possibility of a memory application is also investigated.

The MOSFET structure in the experiment is similar to that of a Flash memory and composed of a transistor with a SNO film employed as an intermediate gate insulator. The SNO film is sandwiched between thermal SiO₂ and ALD SiO₂ layers on a p-type silicon substrate. The MOS capacitor is the same gate structure as the MOSFET without Source and Drain (S/D) contacts except that it has an n⁺ silicon substrate.
Figure 1 shows the capacitance-voltage characteristics of a MOS capacitor at various temperatures. The dielectric constant of SNO can be extracted from the structural parameters and capacitance. It is ~ 26 at room temperature. The extracted dielectric constant is in good agreement with optical measurements of the closely related material NdNiO$_3$ [4]. As shown in the figure, the hysteretic behavior of capacitance is observed. Capacitance during a forward sweep increases initially and has a peak value at a certain gate voltage, around -1.6 V and then decreases. During a backward sweep, similar effect happens, but its magnitude is lower. Similar hysteretic behavior was also observed in a SrTiO$_3$ (STO) film. Buniatian, et al., explained that the hysteresis effects are caused by excess space charges, such as oxygen vacancies, and proposed a model based on the Poole-Frenkel charge trapping/de-trapping mechanism [5].

Figure 2 shows the results of peak capacitance variation as a function of frequency. As shown in the figures, the capacitance and its hysteresis window increase as the frequency decreases. This implies that the dielectric constant of SNO changes with the frequency. The permittivity of a dielectric material depends on the frequency of the applied field since there are various polarization mechanisms and each type of polarization has a different response time. For example, space charge polarization has a relaxation frequency of around 100 kHz. In case of SNO, the response time of polarization is over 1 µsec. Therefore, space charge polarization is dominant in the permittivity of the SNO film.

As expected from the results of a MOS capacitor, hysteretic behavior of capacitance between gate and S/D is observed as shown in Figure 3. As the gate voltage is cycled between -10 and 10 V, the capacitance cycles counterclockwise. This hysteretic behavior is consistent with polarization switching effect. Since the threshold voltage shift happens even in the absence of channel current, it is a gate field effect. In addition, it occurs at room temperature. Therefore, this effect is independent of the thermally-driven phase transition of SNO. With the decrease of frequency, threshold voltage decreases substantially, and hysteresis window and inversion capacitance increase slightly. This implies that polarization change makes an effect on the change of threshold voltage dominantly. These results, their existence with a gate field, their existence in the absence of heating, and frequency dependence, can be explained through space charge polarization mechanism in the SNO film.

In measurement of state retention characteristics, capacitance at zero gate bias is monitored after applying a gate pulse to suppress data interference. As shown in Figure 4, the state decays gradually. It is believed that the depolarization field degrades the polarization of a SNO film. The state retention time is of the order of ten seconds.

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