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On the use of GaAs native oxide to characterize MISM and MISIM switching devices

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Two-state bistable switching phenomena in both metal-native oxide-semiconductor-metal (MISM) and metal-native oxide-semiconductor-native oxide-metal (MISIM) structures have been achieved by experimental predictions for the first time, where the GaAs native oxides are formed by the liquid phase chemical enhanced oxidation (LPCEO) technique. Bidirectional two-state switching (DIAC-like) and three-terminal operation are also shown in the optical sensitive MISIM structure. Typical switching voltages for GaAs MISM and MISIM switching devices under 4 nm-thick native oxides are 7 V and 15 V, respectively. The corresponding voltage control efficiencies for MISM and MISIM switching devices are also as high as 3.944 and 7.04.

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1. Introduction

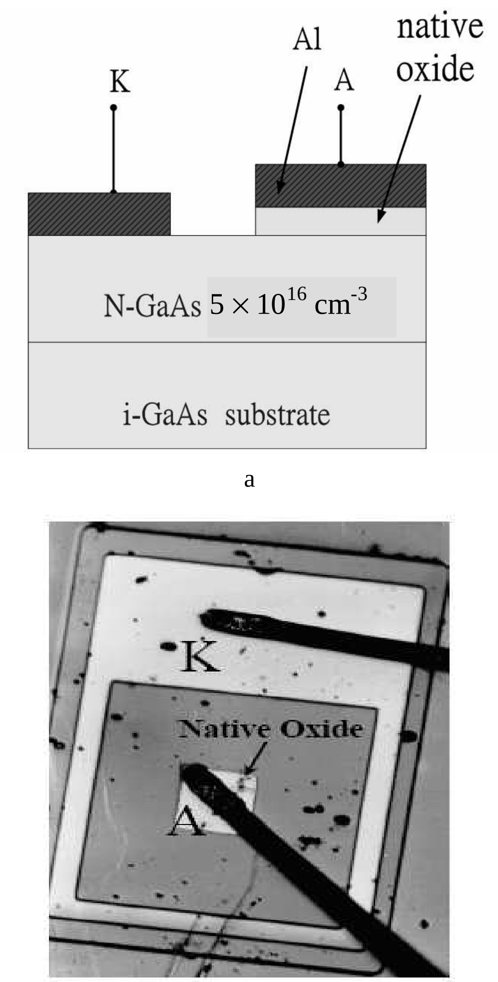
Due to the rapid advances in film growth technologies, such as metal-organic chemical vapor deposition (MOCVD), GaAs regenerative switching devices with NDR phenomena have been widely employed in optoelectronic and logic applications [1-2]. Recently, many devices exhibiting either S-shaped or N-shaped negative differential resistance (NDR) have attracted interests for circuit applications. These NDR devices have long been studied and used as high frequency oscillators and high-speed switches because of their potential for power generation in microwave and millimeter-wave region. Among the S-shaped NDR devices, possible structures are including the triangular barrier pn junction [3-4], metal-insulator-semiconductor (MIS) [5], delta-doping superlattice [6] and heterojunction [7] etc. The switching characteristics can be controlled in either electrical or optical triggering [8].

For conventional Si-based switches, the switching behavior has been observed in metal-insulator (SiO_2)-n-p (MISS) [5] where the regenerative feedback loop is established between the tunnel MIS and pn junction. Then, an alternative MISM structure is also proposed where the pn junction is replaced with the MS Schottky barrier and a reduced minority carrier storage time can be expected. With an extension of two back-to-back MISMs, i.e., MISIM, a bi-directional two-state (DIAC-like) switching characteristic is also exhibited [9-10]. But, unlike Si-based devices, the lack of reliable native oxide limits the GaAs MIS-based device applications. In this report, a liquid phase chemical enhanced oxidation (LPCEO) method [11] is utilized to grow the GaAs MISM and MISIM switches with a nano-scaled native oxide for the first time. Efforts designed to investigate SCR- and DIAC-like switching behaviors using GaAs-based MISM and MISIM with GaAs native oxide as insulator are still limited. The high-speed and high-performance properties can be predicted by using GaAs instead of Si due to the higher mobility and larger energy gap in GaAs material. The GaAs native oxides were formed in a gallium-ion-contained nitric acid solution with an oxidation rate of 60nm/hr. The predicted switching behaviors to occur in MISM and MISIM have been experimentally observed with LPCEO grown native oxides. The fabricated MISM and MISIM devices exhibit SCR- and DIAC-like characteristics, respectively. Because the I-V characteristics are also associated with incident light, the MISIM device exhibits a flexible optical function.

2. Experimental

The cross-sectional view and completed top view of the MISM device are shown in Fig. 1(a) and 1(b), respectively. The studied structures, i.e. MISM and MISIM, were grown by an AIXTRON 2400 MOCVD system on a (100)-oriented i-GaAs substrate, following by a 0.2 μm-thick n-GaAs active layer with a doping concentration of 5×10^{16} cm^{-3}. Silane (SiH_4) was used as the n type dopant. After epitaxial growth of n-GaAs layer, the GaAs sample was immersed into a gallium-ion-contained nitric acid solution to form the GaAs native oxide**.** The key feature of the LPCEO technique is that the formation of native oxides proceeds in a gallium-ion-contained nitric acid solution, which is

PH value controlled with ammonia solution at temperatures ranging from 40°-70 °C. From experiments, it is found that an oxidation rate about 60 nm/hr at 60 °C can be grown on a GaAs surface without any cover. The grown GaAs native oxide is composed of Ga_2O_3 and As_2O_3. The oxidation rate is dependent on the existence of Ga polyoxycation species in the solution [11].



a

b

Fig. 1. (a) Cross-sectional view of MISM structure (b) Top view of the completed MISM device.

In Fig. 2(a), the SEM micrograph shows the sharp and smooth interface between native oxide and metal. The uniformity of native oxide is also depicted in Fig. 2(b). From the AFM micrograph, small mean and rms roughness are 0.45 nm and 0.585 nm, respectively. Thus, the advantage of LPCEO technique is not only easy but also simple in producing high uniformity of GaAs native oxides at low temperature. In addition, the determination of oxide thickness was made by SEM and ellipsometry. Then, the conventional processes including photolithography, vacuum evaporation and chemical wet etching were applied to fabricate the mesa isolation with an area of 6 × 10^{-6} cm^2. The GaAs native oxide can be etched away by using NH_4OH:$1H_2O_2$:$100H_2O$ etching solution. The aluminum (Al) metal used as the hole injector instead of pn junction in these two structures was evaporated over the whole surface and photoresist defined on top of the Al and aligned with native oxide. Experimental current-voltage (I-V) characteristics were measured by a Tektronix 370 A curve tracer and HP 4156 semiconductor parameter analyzer.

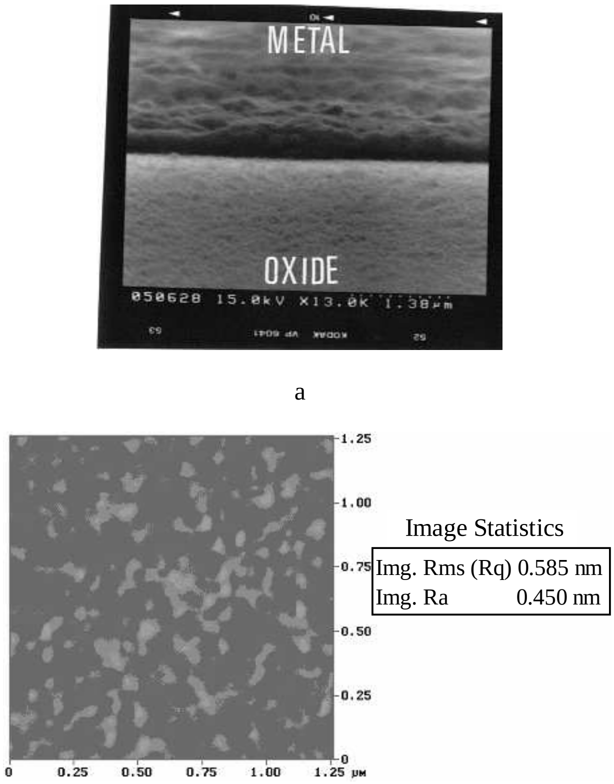


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Fig. 2. (a) SEM micrograph of the native oxide and metal (b) AFM micrograph of the native oxide.

3. Results and discussion

3.1 SCR-like characteristics of GaAs MISM switch

The measured I-V characteristic of the studied MISM switch at room temperature is shown in Fig. 3. The distinguished S-shaped NDR characteristic is observed. The switching parameters are switching voltage V_S = 7.1 V, the holding voltage V_H = 1.8 V, switching current I_S = 0.2 mA, holding current I_H=3.2 mA and the whole voltage control efficiency $\eta=V_S/V_H$= 3.944. This high control efficiency may be used for two-state logic application. Under an appropriate voltage source V_{CC}(= 5 V) and load resistor R_L(=500 Ω), the load line will intersect the I-V curve at stable point Q with (V_Q = 1.9 V, I_Q = 5 mA). The existence of operating point Q shows that the switch may be operated at logic 0 and 1. It is believed that the logic performance can be accomplished with the proper circuit design. In Fig. 3, the thickness of the MISM switch with a GaAs native oxide is 4nm and a separation of 10 μm between two Al electrodes. Fig. 4 shows the switching voltages as a function of thickness of GaAs native oxide. The thicker oxide induces the higher applied voltage to make the electrons to tunnel the barrier in the MIS energy band and then the switching voltage is getting higher. In our experiments, it is found that there is no switching characteristic while the thickness of GaAs native oxide is over 12 nm. This may be explained that there is no tunneling effect if the oxide thickness is too thick. Thus, the I-V characteristics of MISM device are just like a diode while the thickness of GaAs native oxide is over 12 nm in our study.

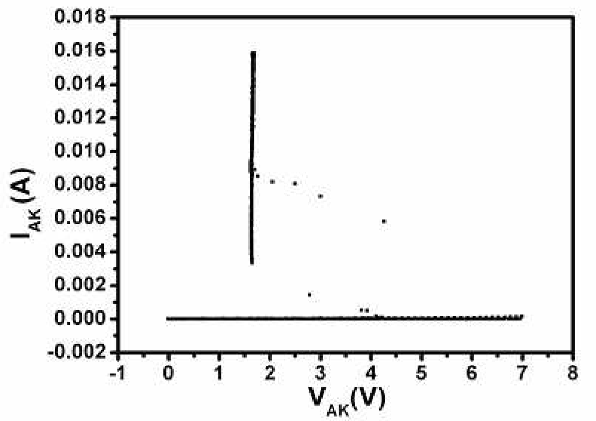


Fig. 3. Two-state switching characteristics for the MISM device.

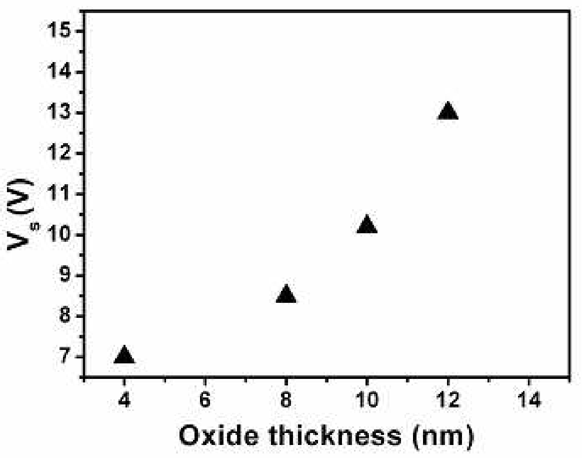
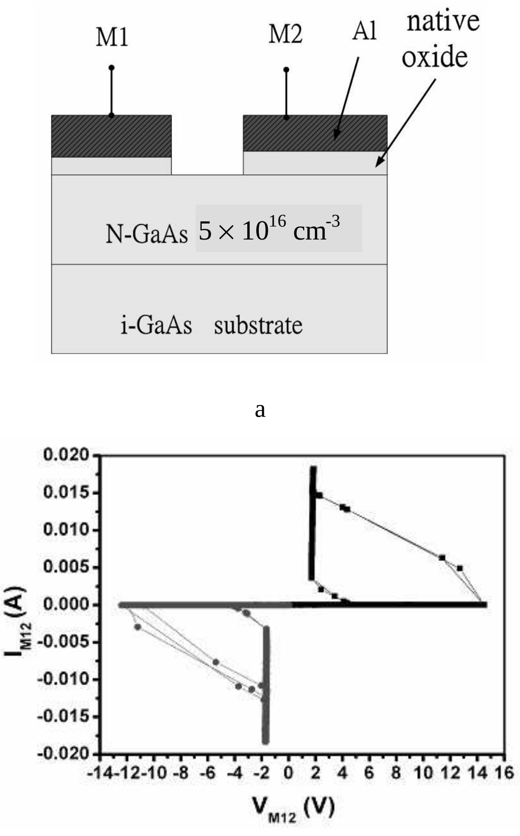


Fig. 4. Switching voltages (V_S) as a function of oxide thickness.

3.2 DIAC-like characteristics of GaAs MISIM switch

Fig. 5(a) shows a schematic representation of the MISIM switch where the native oxides are beneath M_1 and M_2 metals and removed by etching solution with Al as the metal mask. The MISIM structure can be considered as the combination of two MISM back to back in series. The predicted switching in MISIM will show switching in both polarities, i.e. it has a DIAC-like I-V characteristic. Fig. 5(b) depicts the bidirectional two-state characteristic with both oxides also having a thickness of 4 nm and a separation of 10 μm between two Al electrodes. The minor difference between forward and reverse bias is mainly due to the variation of doping in active layer and the smooth of oxide layers. The measured switching parameters in forward condition are the maximum switching voltage V_S = 14.8 V, the holding voltage V_H = 2.1 V, switching current I_S = 0.22 mA, holding current I_H = 2.7 mA and the whole voltage control efficiency $\eta=V_S/V_H=7.04$, which are all better than those in MISM.



a

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Fig. 5. (a) Cross-sectional view of MISIM structure (b) Bidirectional two-state switching characteristics for the MISIM device.

Fig. 6 shows the three-terminal operation of the MISIM switch with the n-GaAs as the third electrode to demonstrate the possibility of voltage-controlled modulation. The effect of biasing the gate negatively with respect to the ground is shown. The effect of the negative gate bias is to increase this forward applied bias, thus injecting electrons towards the grounded electrode. As a consequence of this forward voltage, holes are injected into the n-GaAs, some of them reaching the reverse biased MIS diode. Thus, the switching voltages are reduced while increasing the third gate voltages. In addition, the studied three-terminal MISIM switch is also photo-sensitive. In the inset of Fig. 6, the illumination effects on the switching I-V characteristics of light-illuminated MISIM are demonstrated. The illuminated characteristics are obtained by using a tungsten lamp as the light source. The incident optical power was measured from the photocurrent of the device and then estimated light power is 150 nW. For example, the observed variation in switching voltage after light illumination is from 11.8V to 6.5V at $V_G = 0$. The final switching voltages are all decreased while the light is illuminated on the device due to the generation of electron-hole pairs [12-13].

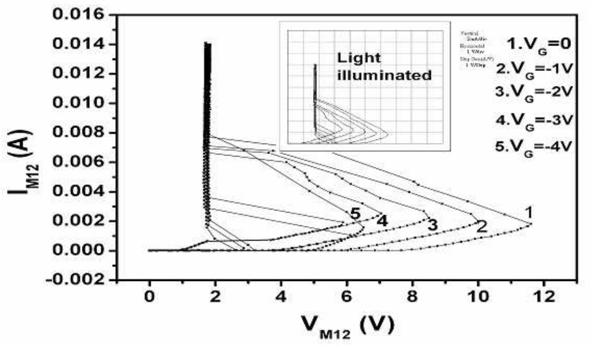

Fig. 6. Dark and light-illuminated (in the inset) three-terminal I-V characteristics of the MISIM device.

4. Conclusions

Uni-directional and bi-directional two-state switching characteristics with three-terminal operation have also been observed. Switching characteristics have been predicted and experimentally investigated in MISM and optically controllable MISIM structures with GaAs native oxides as insulators. Based on the easy and simple LPCEO technology used in fabricating GaAs MIS-based switches near temperature operation, the switches with MISM and MISIM switches may have the potential for high-speed switching applications.

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References

[1] K. F. Yarn, Y. H. Wang, M. S. Chen, Mat. Sci. & Eng. **B35,** 29 (1995).
[2] K. F. Yarn, Y. H. Wang, M. S. Chen, Electron. Lett. **31**, 1063 (1995).
[3] K. F. Yarn, Phil. Mag. **B69,** 1093 (1994).
[4] C. E. C. Wood, L. F. Eastman, K. Board, K. Singer, R. J. Malik, Electron. Lett. **18**, 676 (1982).
[5] T. Yamamoto, M. Morimoto, Appl. Phys. Lett. **20,** 269 (1972).
[6] E. F. Schubert, J. E. Cunningham, W. T. Tsang, Appl. Phys. Lett. **51,** 817 (1987).
[7] K. Hess, T. K. Higman, M. A. Emanuel, J. J. Coleman, J. Appl. Phys. **60,** 3775 (1986).
[8] G. W. Taylor, R. S. Mand, J. G. Simmons, A. Y. Cho, Appl. Phys. Lett. **49,** 1406 (1986).
[9] M. Darwish, K. Board, Electron. Lett. **16,** 577 (1980).
[10] K. F. Yarn, Y. H. Wang, C. Y. Chang, J. Appl. Phys. **75,** 2695 (1994).
[11] H. H. Wang, C. J. Huang, Y. H. Wang, M. P. Houng, Jpn. J. Appl. Phys. **37,** L67 (1998).
[12] K. F. Yarn, Y. H. Wang, C. Y. Chang, M. S. Jame, IEE Proc. **134,** 129 (1987).
[13] K. F. Yarn, Y. H. Wang, C. Y. Chang, Appl. Phys. A**50,** 485 (1990).

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