Memristive GaN ultrathin suspended membrane array

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Abstract
We show that ultrathin GaN membranes, with a thickness of 15 nm and planar dimensions of $12 \times 184 \, \mu m^2$, act as memristive devices. The memristive behavior is due to the migration of the negatively-charged deep traps, which form in the volume of the membrane during the fabrication process, towards the unoccupied surface states of the suspended membranes. The time constant of the migration process is of the order of tens of seconds and varies with the current or voltage sweep.

Keywords: memristor, GaN, semiconductor membranes

(Some figures may appear in colour only in the online journal)

1. Introduction

Although the memristor was predicted a long time ago, experimental evidence of it only occurred when nanotechnologies had reached a certain degree of maturity. A memristor is a unique circuit element, the fourth fundamental circuit element, which plays a similar role to the inductance ($L$) and capacitance ($C$). Unlike the inductance and capacitance, however, the memristor is a nonlinear circuit element, displaying a voltage–current dependence with a distinct footprint—a pinched hysteretic behavior of the current when the voltage is varied from negative to positive values [1]. Moreover, the resistance of the memristor depends strongly on the history of the applied voltage. Since the memristor remembers its previous state when the excitation is off, it is non-volatile and strongly related to resistive switching memories, which are considered to be the next generation of electronic memories. As such, memristors could be used in reconfigurable logic circuits [2] or in neuromorphic systems [3] in order to mimic the synapses, which are the fundamental key components of neural systems.

These and other applications have initiated a rush for inventing various memristive devices, with several memristor classes being already identified. For instance, there are CMOS-compatible memristors based on (i) resistive switching memories in oxides such as TiO₂ and WO₃, (ii) electrochemical metallization (redox memristors), and (iii) phase change materials [4, 5]. The memristive behavior is encountered in many materials, in which different physical effects are present. The ultimate memristor is a gate-tunable single atomic sheet of matter such as MoS₂, in which the memristive behavior is due to the variation of carrier density as a function of the gate voltage [6].

GaN, also termed ‘new silicon’, is presently the second most important semiconductor after Si, and has well-known applications in high-frequency and power electronics. In the form of nanowires and nanotubes, GaN has an increasing number of applications in the area of nanoelectronics [7]. GaN memristors would further increase the applications of...
this material in applied physics and nanotechnologies. The imprint of memristive phenomena in GaN could be traced in effects of unipolar [8] and ambipolar resistive switching [9] in amorphous GaO, where the effect is due to the formation/rupture of conductive filaments that form due to oxygen vacancies or to the field-induced migration of oxygen vacancies, respectively, as well as in bipolar switching of the metal–insulator AlN/n-GaN structure [10] due to a trap-controlled space charge current. In the GaN membrane arrays presented in this paper, the memristive behavior is a combined mechanism, in which both trap migration and trap-controlled space charge contribute to the observed voltage and time dependencies of the current.

2. Fabrication of GaN membranes

The GaN memristive device reported in this paper was fabricated using a modified version of the surface charge lithography (SCL) that is well described in [11, 14] and will not be repeated here in detail. We note that the SCL is based on ion-beam-writing of surface negative charge followed by photo-electrochemical (PEC) etching of the GaN layer. The ultrathin GaN membrane array was fabricated on the same MOCVD-grown GaN layer by treating some regions with 0.5 keV Ar$^+$ ions at the dose of $10^{11}$ cm$^{-2}$, as described in [11, 12].

The metallic Ti/Au ohmic contacts were deposited on as-grown GaAs via photo-lithographically defined windows. First, 50 nm Ti was deposited using electron beam evaporation from a Ti wire, followed by thermal evaporation of 200 nm thick Au (TedPella 99.99%). The lift-off process was followed by 0.5 keV Ar$^+$ ion treatment with subsequent etching of the samples, resulting in the ultrathin suspended GaN membranes. In the ion-treated regions conductive GaN membranes are formed, as shown in figure 1(a). In this way, we can fabricate suspended GaN membrane arrays separated by nonconductive paths. The thickness of the GaN membrane measured using SEM was found to be 15.6 nm. The SEM of the cross-section of the device, shown in figure 1(b), reveals that the GaN membranes are sustained by a network of pillars formed by nanowires that represent threading dislocations [11]. As will become clear in the following, this way of fabricating GaN membrane arrays is at the origin of the memristive phenomena investigated in this paper.

In [14] it is shown that the diffraction pattern of GaN membranes as those used in this paper displays a wurtzite crystalline structure. A further structural characterization was performed using high-angular dark field scanning transmission electron microscopy (HAADF-STEM) using a FEI Titan 80/300 instrument equipped with a corrector for spherical aberration of objective lenses and a Fishione model HAADF detector. The SEM image taken from a piece of a broken membrane reveals details of the spatial architecture (see figure 2(a)), while the STEM image in figure 2(b) reveals the crystalline structure of the membrane. The thickness of the GaN membrane estimated by STEM was 15 nm, similar to the value determined by SEM analysis.

3. Measurements and discussions

The $I$–$V$ dependence of the suspended GaN membrane array was measured using a semiconductor characterization system Keithley 4200 SCS. The DC probes connected to the Keithley 4200 were placed together with the probe station in a Faraday cage provided by Keithley and all measurements were taken at room temperature. Figure 3 illustrates the experimental setup, while the current–voltage dependence at consecutive sweeps is represented in figure 4. The voltage is swept first from $-5$ V up to $+5$ V and then backwards, from $+5$ V to $-5$ V. This procedure is repeated several times, the successive sweeps being marked on figure 4 as 1, 2, 3, and 4. It can be seen that the GaN membrane array behaves like a memristor because the $I$–$V$ dependence in the range $-5$ V to $+5$ V is strongly nonlinear and has a pinched hysteretic shape. Moreover, at consecutive sweeps the initial pinched hysteresis is shifted towards higher currents but preserves its shape, illustrating clearly another property of the memristor: memory, i.e. dependence on the previous state. We have investigated several devices, with membranes widths varying by few nanometers, as evidenced by SEM. We have performed
electrical characterization on several devices and for different voltage steps, and have not introduced any smoothing procedures intentionally, neither in the DC measurement station computer nor in the computed results after measurements. We have not observed any significant changes in the current–voltage dependencies in different experimental conditions.

Similar increases of the current at successive voltage sweeps have been observed in other materials as well, and have been explained by a trap-controlled space charge limited current mechanism [15], in which negatively-charged deep traps generate electric fields with the same orientation as the applied fields. In order to investigate the possibility that charge transport in our device is determined by the same mechanism, we have represented in figure 5 the dependence log(I) versus log(V) for the first and the fourth sweep in figure 4, looking for the value of $\alpha$ in the relation $I = V^\alpha$. As can be seen from figure 5, the $\alpha$ values are practically the same for the first and the fourth sweep. For low applied voltages $\alpha \leq 1$, which corresponds to an ohmic behavior, while for higher voltages the nonlinearity increases, the values of $\alpha$ increasing continuously up to about 4. These values are consistent with a space charge limited current
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mechanism [10, 13], in which the electric field induced by the negatively-charged deep traps enhances the applied field. In the case of the GaN membrane array, the negatively-charged deep traps are formed during irradiation by Ga\(^{+}\) ions.

Figure 6 represents the dependence of the current on time at the same applied voltage of \(-7\) V, maintained constant during the experiment, the data being collected over 3 min for five consecutive time sweeps. From figure 6 it can be seen that at each sweep the amplitude of the current increases, although the applied voltage remains the same. The respective voltage–time dependence at constant current, illustrated in figure 7, shows a decrease of the voltage in time. The compatible time dependencies of both current and voltage can be explained by an electric-field induced migration of trapped negative charges towards the surface states of the membrane. The migration is only observed for sufficiently high applied voltages or currents, for which the barriers confining the trapped charges decrease; we have not observed a consistent time variation of currents and/or voltages for smaller values of voltages/currents than those in figures 6 and 7, which suggests that the time dependencies are not a result of a simple detrapping process. The time constants associated to the migration of trapped charges are different for different sweeps. For instance, for the first to the fifth sweeps in figure 6 they are: 9.3 s, 18.2 s, 17.5 s, 15.8 s, and 11.2 s, respectively, while the corresponding migration times for the first and the second sweep in figure 7 are 40 s and 69 s. The increase of the migration time from the first to the second sweep reflects the migration to the slight decrease of this parameter for further sweeps and could be attributed to the build up of an electric field close to the edges of the membrane that could accelerate the migration of the remaining trapped charges.

So, due to the increasing applied electric field, the charges trapped in the membrane volume migrate towards the membrane surface and fill the surface states, thus increasing the current. The surface states are filled gradually, the current increasing progressively at each constant voltage cycle. The minimum resistance value, denoted by \(R_{\text{ON}}\), corresponds to the situation when all surface states are filled due to charge migration whereas the maximum value of this parameter, \(R_{\text{OFF}}\), is associated to the case when no surface state is filled, i.e. the device is in the initial state. The charge migration in our GaN membranes is analogous to the drift of oxygen vacancies, seen as positively-charged dopants, in the first memristor, based on a TiO\(_2\) oxide layer with a thickness of 5 nm sandwiched between two Pt contacts [16]. In the latter case, \(R_{\text{ON}}\) and \(R_{\text{OFF}}\) are attributed to doped and undoped states of the TiO\(_2\). Based on this analogy, the time dependences of the current–voltage characteristics can be described as [3, 16]:

\[
i(t) = \frac{v(t)}{R_{\text{ON}}\gamma(t) + R_{\text{OFF}}(1 - \gamma(t))}
\]

where \(\gamma(t)\) is a continuous time function with values in the [0,1] domain. The function \(\gamma(t)\) reaches its maximum and minimum values, of 1 and 0, when \(R = R_{\text{ON}}\) and, respectively, \(R = R_{\text{OFF}}\). \(\gamma(t)\) is considered as a linear function of the flux linkage \(\Phi(t) = \int v(t)\,dt\) [3], so that the memristor equation as defined initially by Chua is retrieved. Equation (1) determines the equivalent circuit of the GaN membrane memristive device as being formed from two variable resistances connected in series, like in [16]. In the case of our membranes, \(R_{\text{ON}} = 806 \, \Omega\) and \(R_{\text{OFF}} = 77 \, k\Omega\), the ratio \(R_{\text{OFF}}/R_{\text{ON}}\) reaches a value of 95.

Regarding the power supported by the GaN membrane, the maximum power estimated from the data in figure 4 is about 6 mW at 5 V in the first sweep and 10 mW in the fourth sweep. However, we have experimentally determined that a single GaN membrane can support currents as high as 60 mA at 9 V, and thus a power of 540 mW, with no signs of failure being observed during the measurements. The reason is that the GaN wurtzite crystal combines two essential physical properties for high-power applications: a large bandgap, of 3.4 eV, and a high thermal conductivity, of 1.3 W cm\(^{-1}\) K\(^{-1}\). ```
at room temperature. Therefore, besides the many high-power circuits and integrated circuits currently based on GaN, the GaN membrane memristor reported in this paper is a high-power device compared to other memristors reported in the literature. Because the metallic contacts with the sample are ohmic and the membrane is supported on isolator pillars, the electrical losses in the device are negligible.

4. Conclusions

In conclusion, the GaN membrane array behaves like a memristor as a result of the fabrication method, which on one hand produces defects in the GaN membrane that trap negative charges, and on the other hand creates a very large number of unoccupied surface states, much larger than the number of defects. Under the action of the electric field, the trapped charges in membranes migrate by hopping or tunneling from one defect to another until they reach the surface states. The surface states are increasingly filled with electrons at every voltage sweep, the consequence being an increase in the current, as shown in figure 4, as a result of a decreased screening of the applied electric field. It is clear from figures 6 and 7 that the memristor memorizes its previous state, but at each sweep the current and the voltage vary in time due to the fact that the number of trapped negative charges in the volume decreases as a result of their migration to the surface states. The time evolution of the current and voltage takes place until all volume trapped charges migrate towards the surface. This delicate balance between trapping and hopping/tunneling, defects and surface states, is at the origin of the behavior of the GaN membrane array memristor.

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References

[1] Chua L 2014 If it’s pinched it’s a memristor Memristors and Memristive Systems ed R Tetzlaff (New York: Springer) pp 17–90
[2] Xia Q 2014 Memristor device engineering and CMOS integration for reconfigurable logic applications Memristors and Memristive Systems ed R Tetzlaff (New York: Springer) pp 195–221
[3] Jo S H, Chang T, Ebong I, Bhadviya B B, Mazumder P and Lu W 2010 Nanoscale memristor device as synapse in neuro morphic systems Nano Lett. 10 1297–301
[4] Yang Y, Chang T and Lu W 2014 Memristive devices: switching effects, modeling, and applications Memristors and Memristive Systems ed R Tetzlaff (New York: Springer) pp 195–221
[5] Wouters D J, Waser R and Wuttig M 2015 Phase-change and redox-based resistive switching memories Proc. IEEE 103 1271–88
[6] Sangwan V K, Jariwala D, Kim I S, Chen K-S, Marks T J, Lauhon L J and Hersam M C 2015 Gate-tunable memristive phenomena mediated by grain boundaries in single-layer MoS2 Nat. Nanotechnol. 10 403–6
[7] Law M, Goldberger J and Yang P 2004 Semiconductor nanowires and nanotubes Annu. Mater. Res. 34 83–122
[8] Guo D Y et al 2015 Unipolar resistive switching behavior of amorphous gallium oxide thin films for nonvolatile memory applications Appl. Phys. Lett. 106 042105
[9] Guo D Y, Wu Z P, Zhang L J, Yang T, Hu Q R, Lei M, Li P G, Li L H and Tan W H 2015 Abnormal bipolar resistive switching behavior in a Pt/GaO1.3/Pt structure Appl. Phys. Lett. 107 032104
[10] Chen Y, Song H, Jiang H, Li Z, Zhang Z, Sun X, Li D and Miao G 2014 Reproducible bipolar resistive switching in entire nitride AlN/n-GaN metal-insulator semiconductor device and its mechanism Appl. Phys. Lett. 105 193502
[11] Tiginyanu I, Popa V and Stevens-Kalceff M A 2011 Mater. Lett. 65 360–2
[12] Tiginyanu I M, Popa V and Stevens-Kalceff M A 2011 Nanoperforated and continuous ultra-thin GaN membranes Electrochem. Solid State Lett. 14 K51–4
[13] Tiginyanu I M, Popa V, Stevens-Kalceff M A, Gerthsen D, Brenner P and Pavlidis D 2012 Design and maskless fabrication of ultrathin suspended membranes of GaN Phys. Status Solidi RRL 6 149–50
[14] Volosciuc O, Sergentu V, Tiginyanu I, Schowalter M, Ursaki V, Rosenauer A, Hommel D and Gutowski J 2014 Photonic crystal structures based on GaN ultrathin membranes J. Nanoelectron. Optoelectron. 9 271–5
[15] Obreja A C, Cristea D, Mihalache I, Radoi A, Gavrila R, Comanescu F and Kuskó C 2014 Charge transport and memristive properties of graphene quantum dots embedded in poly(3-hexylthiophene) matrix Appl. Phys. Lett. 105 083303
[16] Strukov D B, Snider G S, Stewart D R and Williams R S 2008 The missing memristor found Nature 453 80–3