Communication

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An AlN Switchable Memory Resistor Capable of a 20-MHz Cycling Rate and 500-picosecond Switching Time

Abstract: We report here the operational characteristics of multistable resistance switching devices made from thin sputtered layers of AlN. These devices exhibit switching between high and low resistance states when proper electrical signals are applied. Repetitive switching at 20-MHz rates has been achieved, and switching times in the best units have been observed to be less than 500 picoseconds. These are believed to be the first active electronic switching devices to be reported utilizing AlN.

Introduction

We have observed electrical switching and memory effects in thin sputtered films of AlN, and we report here the operational characteristics of multistable resistance switching devices which are made from these AlN films. AlN is a refractory material with a bandgap of 5.9 eV, one of the widest gaps reported for semiconductor materials [1]. Although numerous reports of the electrical properties of bulk AlN and AlN films have been published [1–6], we believe that the present work is the first report of active electronic switching devices made from this material.

We have obtained the following results, which are discussed in detail in this paper: 1) Switching and memory effects are typically observed in sputtered AlN layers on W or Mo substrates, with Si or Al counter-electrodes. 2) Such layers exhibit transitions between high (typically 10^4 Ω) and low (typically 100 Ω) resistance states when electrical signals of suitable polarity, magnitude, and duration are applied. 3) Repetitive switching at rates up to 20 MHz has been observed, generally between states with impedance ratios of about 10:1. These switching rates are more than an order of magnitude faster than those reported for devices with similar characteristics made from other materials. 4) These devices exhibit memory; that is, devices remain indefinitely in either impedance state when voltage is removed. 5) On the best units, switching times in both directions have been observed to be less than one nanosecond, with the fastest transition less than 500 picoseconds.

The physical mechanism responsible for the phenomena described here is at present not understood; however, of the many multistable resistance effects reported in the literature in recent years [7], the effects we observe in AlN seem to resemble most closely those observed in various semiconductor heterojunctions by H. Hovel of this laboratory [7]. It is possible that a common explanation may apply to the effects observed by Hovel and those reported here. At any rate, the purpose of the present paper is to present operational characteristics of devices prepared from these AlN films, rather than to discuss the underlying physical principles involved.

Device preparation

Early AlN switching devices were made by pyrolytic vapor deposition of single crystal layers of AlN, 6 μm thick, on highly doped single crystals of SiC [8]. These refractory materials have closely matching lattice parameters and have been known to grow epitaxially at elevated temperatures [9]. Contact to the AlN layer was made by alloying silicon pieces approximately 5 mils in diameter to the AlN surface at temperatures between 1500°C and 1800°C in a nitrogen or argon forming gas atmosphere. Silicon has been found to be one of the few materials that wets AlN readily. The solubility of silicon in AlN is very low in the temperature range used. When the silicon contact is etched away after being wetted to the AlN surface, an only slightly visible stained area

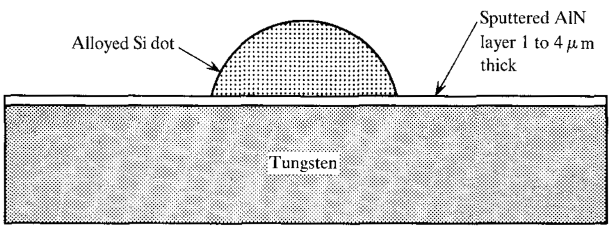
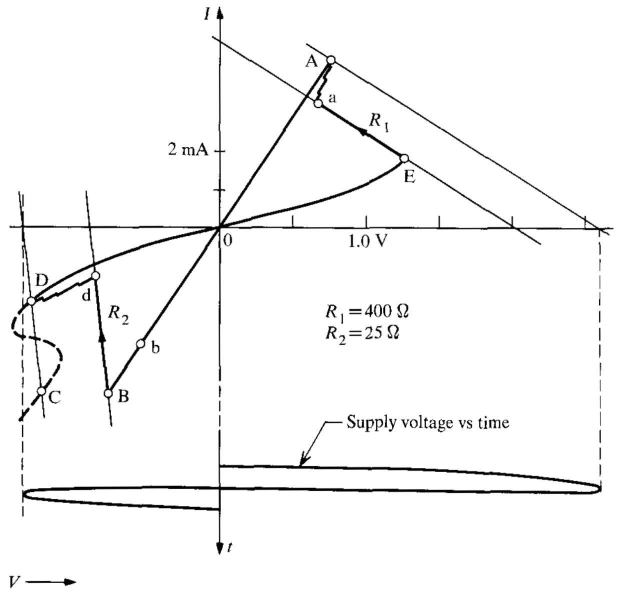


Figure 1 Device structure.

Figure 2 *I*–*V* characteristics of a typical unit. The forward direction corresponds to positive voltage on the silicon counterelectrode (see Fig. 1).



remains, indicating that any recrystallized region, if it exists at all in the AlN, is extremely thin. Units made in this way showed capabilities of operating in a low-impedance state of 4 Ω up to currents of 1 ampere and a high-impedance state of 1000 Ω with a switching voltage of 18 V. However, due to the slight difference between the thermal coefficients of expansion of AlN and SiC, the layers of AlN often cracked in the fabrication process. Subsequently, it was found that a device with similar operating characteristics could be made from layers of AlN reactively sputtered by F. d'Heurle of this laboratory on molybdenum or tungsten (refractory metals with suitable coefficients of expansion), again with contact to the AlN being made by alloying silicon or other conducting materials, notably aluminum, to the AlN surfaces. Figure 1 shows a cross-section of a typical unit.

The sputtered devices are more easily fabricated and can be made free of cracks. AlN has been reported to have been grown by reactive dc sputtering of aluminum in argon and nitrogen mixtures [3]. In the present work, AlN is reactively rf sputtered in pure nitrogen from a 99.999% pure aluminum target with an rf driven bias on the substrates. Typically the sputtering system's initial pumpdown pressure is 2×10^{-8} Torr, where substrates are outgassed at 1100°C. Aluminum is presputtered in argon for 1 hour, after which nitrogen is introduced and substituted for the argon and presputtered for an additional 1/2 hour. The substrates are sputter-cleaned in argon for 10 minutes while they are at an elevated temperature; nitrogen is then introduced, replacing the argon, and sputter deposition takes place. The deposition temperature for epitaxial growth is 1100°C at a power density of 8 W/cm^2 with an rf driven bias of −50 V dc applied to the substrates.

The substrates on which working devices have been made are polycrystalline and single crystal (111) W, (111) Si, (0001) SiC, and (111) Mo. In this report we are primarily concerned with devices made on W substrates with AlN layers about 1–2 μm thick to which a silicon counterelectrode has been alloyed. AlN layers deposited on polycrystalline tungsten are polycrystalline, with a typical grain size of about 500 Å. AlN layers deposited on (111) single crystal W exhibit a greater degree of perfection, being approximately single crystal although with a high dislocation density as evidenced by etch patterns. No pronounced difference has been observed in the electrical characteristics of the devices made from the two types of tungsten substrates.

AlN thin film devices fabricated as described above show initially a very high impedance ($>10^9\ \Omega$) and generally require electrical forming (that is, the application of a high voltage, compared with subsequent switching voltages, which switches the device to a low resistance state) before they demonstrate switching and memory effects. Forming is a "one-step" process; after the forming operation, the device has the electrical properties described in subsequent sections of this paper. The forming voltage is typically 50 V and is about the same for different devices made on the same substrate. However, the forming voltage varies considerably from substrate to substrate; some devices require several hundred volts, others need essentially no forming. The reason for this is not known; the variation does not appear to be directly correlated with AlN film thickness.

Device I-V characteristics

Figure 2 shows the *I*–*V* characteristic of a typical unit, as measured by means of the test circuit shown in Fig. 3. This circuit has the capability of producing an asymmetrical driving voltage at the device and also can have different load lines in the forward and reverse directions (as indicated by the slopes of the lines R_1 and R_2 in Fig. 2). Let us now consider the time development of the *I*–

V trace of Fig. 2 when an oscillatory waveform is applied. Assume that the device is in a high impedance state (line D–E in Fig. 2), and at time zero, the driving voltage is zero and initially increases in the positive direction (positive voltage on the Si counterelectrode) as time increases from zero as shown. For the particular driving waveform shown, the characteristic will be the heavy line loop path OEaABdDO. The voltage at point E is the threshold voltage for switching from high to low resistance, and the current at point B is the threshold current for switching from low to high resistance. A salient feature of the loop taken at high frequencies (>100 kHz) is that the absolute value of the switching current I_B tends to be the same as the highest current I_A to which the device was swept after switching from the high impedance state.

The transitions from high to low resistance and from low to high resistance often do not occur in a single step. Referring to Fig. 2, we observe that the high-to-low transition consists of the large step E–a, followed by a number of small steps to still lower resistance values as the supply voltage increases further. The final state of the device (line A–B in Fig. 2) is the state reached by the device when the supply voltage has reached maximum amplitude.

Another feature of the $I-V$ characteristic taken in this way is a tendency for the switching points (E, A, B, and D) to be different for subsequent cycles of the driving voltage. This is particularly noticeable at very low frequencies in the 0-to-100 Hz range. At frequencies in the megahertz range, this variation or jitter in switching points tends to become very small; this allows measurement of the transition or switching times to be made with fast sampling oscilloscopes. On the best units these times have been resolvable to be less than 500 picoseconds. With the testing circuit now used, devices operated at driving frequencies as high as 21 MHz show definite switching loops.

The stability of the switching loops at high frequencies has been demonstrated by continuously operating a unit, with a loop that showed a 4:1 impedance ratio, at 10^6 Hz for 47 hours (more than 10^{11} cycles of operation). Also, the switching loop of a unit operating at 10^6 Hz was observed to be nearly independent of temperature between 200 K and 400 K.

We have not made similar long-duration tests at other frequencies, but on the basis of our experience with these devices it is likely that similar results could be obtained at any frequency in the range from 100 kHz to 10 MHz. Above 10 MHz, stable operation requires more sophisticated circuitry, and we have not achieved repetitive switching above 21 MHz [10]. This is thought to be a circuit limitation, however, rather than a fundamental device property. At low frequencies (less than about 100 kHz), jitter in the switching characteristics makes long-duration stability more difficult to achieve. These measurements of long-duration stability were made simply by periodically observing the device $I-V$ trace, which was continuously displayed on either a real-time or sampling oscilloscope; no attempts were made to count missing cycles (which would require much more complex circuitry). However, the oscilloscope traces during these texts were so stable that it is highly unlikely that there was any appreciable number of missed cycles.

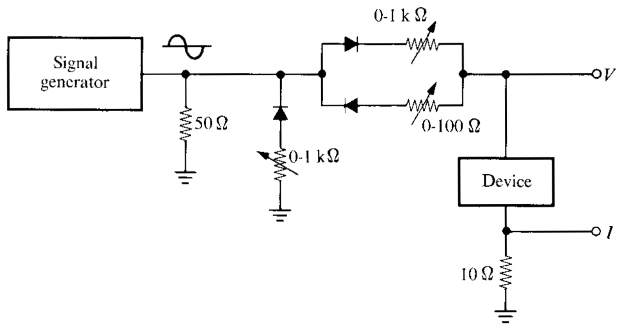


Figure 3 Test circuit.

For fixed load lines and driving waveform, the impedance ratio between the high and low states is greatest at very low frequencies and diminishes as the frequency is increased, generally with the high-impedance state being greatly reduced in value. Thus, while at a low driving frequency of 10 Hz the impedance ratio may be as high as 1000:1 or higher, at a megahertz the ratio is more typically 10:1.

It is important to note that each device has a very large number of intermediate impedance states associated with it. Generally speaking, the intermediate states have lower threshold voltages than states with very high resistance (greater than 10 kΩ) and lower threshold currents than states with very low resistance (less than 100 Ω). These states are accessible in the following way (see Fig. 4): Assume that the supply voltage waveform is as shown (forward amplitude V_1; reverse amplitude V_2); then the outer loop BdDEaAB will be swept out by the device. However, if the reverse amplitude is reduced to V_2', then the smaller loop BdE′a′AB (shaded in Fig. 4) will be swept out; that is, the high resistance states such as DOE will be omitted. These high resistance states are also those which disappear from the loop at high fixed driving frequencies and hence seem to have relatively long time constants associated with them. It is evident that if the forward amplitude is reduced, a similar compression of the loop will occur; this time the device occupies a new "low" resistance state with higher resistance and a smaller threshold current than before. Thus, the shape and size of the traced-out loop changes as the

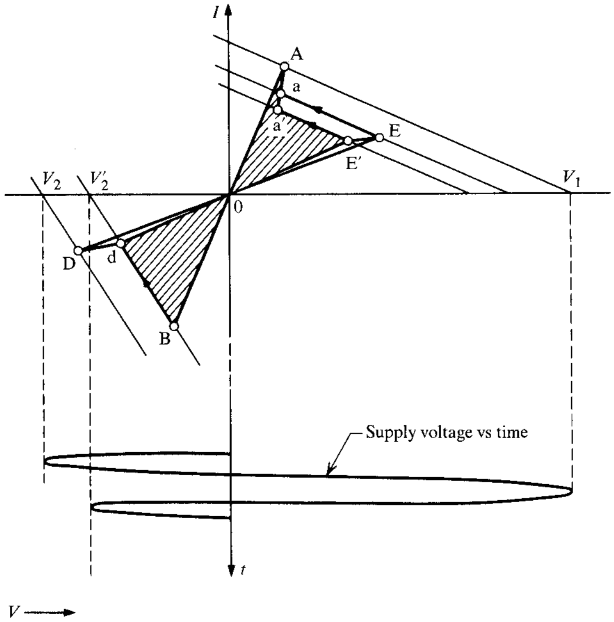
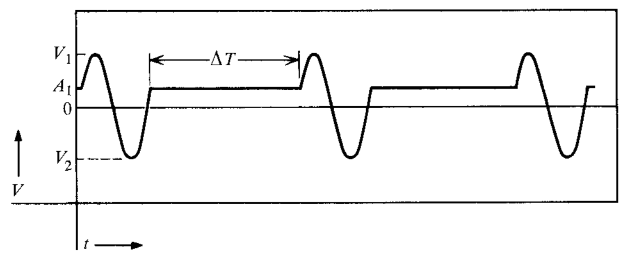


Figure 4 $I-V$ characteristics showing the effect of reducing supply voltage amplitude in reverse direction.

Figure 5 Waveform used for studying stability of $I-V$ characteristics and memory effects as a function of quiescent voltage amplitude (A) and duration (ΔT). The bias point A_1 could be set at any point between V_1 and V_2, and ΔT was varied between 0 and 1 ms.



supply waveform amplitudes change. If the change is too great the device will cease switching and lock into a single impedance state.

Memory effects

One characteristic of the device is that, once switched to a particular impedance state, it will retain this state for long periods of time if the voltage is reduced to zero. States with high impedance are the most stable, although units adjusted to a low-impedance state have been observed to retain this at zero bias for periods of more than 9 months.

We have performed some experiments using not a continuous waveform, but one in which the complete cycle of switching is repeated after intervals of time variable from zero up to a thousand times the single complete cycle switching time. This was done by using a generator in which the quiescent voltage or bias point can be arbitrarily set as shown in Fig. 5.

Thus, the voltage can be held between switching pulse cycles at any point such as A_1 indicated in the figure. This gives a mapping of the stability of bias points other than zero bias. The results of an experiment in which the switching cycle time was 1 μs and the interval between switches was 1 ms can be explained by referring back to Fig. 2. When biased at point A, the characteristic tended to go toward a still lower impedance state, but the switching loop remained essentially unchanged otherwise. Likewise, by biasing at point D the high impedance state tended to become still higher, with the switching loop retaining essentially the same shape. However, biasing at point b made the device switch at a lower current; in fact, for sufficiently long bias duration ΔT, the switching point became point b. That is, the memory of the low-impedance state was disappearing, or at least the range of value of current over which it originally existed was becoming narrower.

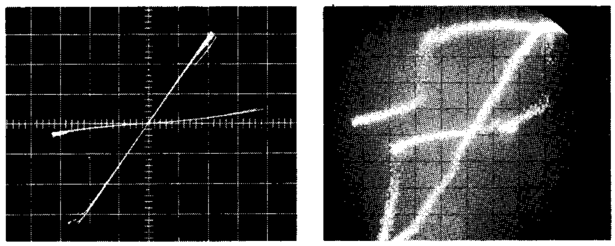
A final word should be said about the extension of the high-impedance state in Fig. 2, indicated by the dashed line. It is a negative resistance "tail" which occurs if the driving voltage is swept sufficiently far in the negative direction, or if the switching point B and resistance R_2 are such that the device switches to this part of the characteristic from the low-resistance state. If switching is done at frequencies lower than about 1 kHz, the $I-V$ characteristic in this region is generally quite noisy, and weak infrared light emission is observed from the device. Also, it has been possible to bias with a large resistor into the negative resistance region and produce self-excited oscillation at frequencies of several megacycles. $I-V$ characteristics for a device operating at 1 kHz and at 10 MHz are shown in Fig. 6. In Fig. 6(a), the device was being swept around the $I-V$ loop at a 1-kHz rate. Note that there were small variations in the switching characteristics from cycle to cycle. In Fig. 6(b), which was obtained by using a sampling oscilloscope, the device was operating at 10 MHz. In addition to the $I-V$ characteristic, a trace of current vs time is shown in the same photograph. The current scale is the same as for the $I-V$ characteristic and the time scale is 1 ns-cm^{-1}. The oscilloscope trigger delay has been adjusted so that the portion of the cycle containing the switching transition from high to low resistance is displayed in the current vs time trace. This transition appears as a nearly vertical rise in current for the time scale used in this photograph and is essentially complete after about 500 ps.

Summary and conclusions

In summary, we have discussed here the properties of multistable resistance switches constructed from sputtered AlN films. This is the first reported use of AlN, a very wide band-gap refractory material, in active electronic switching devices. Devices made thus far have a distinctive characteristic which can be switched from high to low to high impedance states displaying memory by alternate application of positive and negative voltages in a well-defined way. However, care must be taken to use appropriate values of resistance for the load lines and in general to use asymmetrical voltage waveforms. Very high impedance states are associated with low frequencies and more erratic operation. At high frequencies (> 1 MHz) the switching loop can be essentially jitter free, with impedance ratios of about 10:1. Switching times have been resolvable to less than 500 picoseconds, and devices have been repetitively switched at megahertz rates for 10^{11} cycles without detectable change in $I-V$ characteristics.

An obvious application for these devices is to use them as computer memory elements, an application which they share with other bistable resistance devices. However, the very fast switching characteristics suggest other applications such as high speed pulse generation and harmonic generation. The high-current capability and refractory nature of the materials and the very small change in device characteristics with temperature could be useful in power supply applications (for example, as a fast electronically resettable circuit breaker) where severe environmental conditions prevail. Also, the fact that a very large number of stable resistance states is accessible by a definite switching sequence suggests that new applications may be invented.

A discussion of potential applications for this device is of necessity quite tentative, since little is known at present about the physical principles underlying device operation. Likewise, the limits of voltages and currents obtainable, as well as those of the operating speeds and power handling capabilities, are dependent upon fabrication procedures that are still in an exploratory stage and not yet well defined. The attractive aspects of the device described here indicate that it is worthy of further study to determine the physical principles and limits of device operation.



(a) (b)

Figure 6 (a) $I-V$ characteristic of a unit operating at a 1-kHz repetition rate. (Vertical scale: 0.8 mA/cm; horizontal scale: 500 mV/cm.) (b) $I-V$ characteristic (vertical scale: 0.8 mA/cm; horizontal scale: 200 mV/cm.) and current vs time trace (vertical scale: 0.8 mA/cm; horizontal scale: 1 ns/cm.) for a unit operating at 10 MHz. The zero level and deflection sensitivity are the same for the current scales of both traces. In the current vs time trace, the triggering has been adjusted so that the switching transition from high to low resistance is displayed.

References and notes

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10. *Note added in proof:* We have recently achieved repetitive switching at cycling rates as high as 40 MHz in these devices.

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