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SUB-300 MILLIVOLT OPERATION IN NONVOLATILE 300 NM X 100 NM PHASE CHANGE NANOELECTROMECHANICAL SWITCH

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ABSTRACT

This paper reports the design, fabrication, and characterization of the Fin Phase Change Nanoelectromechanical Relay (FinPCNR), a truly nanoscale switch. We harness the nonvolatile volume transformation of GeTe, a widely used phase change material, to drive the laterally actuating relay. The PCNR is turned ON by applying a sub-300 mV short actuation pulse (< 500 ns) to a fin-shaped heater (l: 300 nm, w: 100 nm, h> 100 nm). Novel nanofabrication techniques are developed to self-align multiple functional vertical layers on the heater sidewall. In the OFF state, we achieve near zero leakage (23 fA) by maintaining a sub-5 nm airgap between the metal channel and the drain/source electrodes. This device is an ideal candidate for high density, ultra low-leakage memory circuitry as it combines the nonvolatility of GeTe and the high ON-OFF current ratio of NanoElectroMechanical (NEM) relays.

KEYWORDS

Phase Change Materials, NEM Relay, GeTe, Emerging Memory, Nonvolatility.

INTRODUCTION

Complementary metal oxide semiconductor (CMOS) technology has been at the core of all computing devices for the last five decades. Aggressive scaling of CMOS devices has led to the high efficiency, speed and performance of both processing and memory units in today's computers. As current CMOS technology is projected to reach its scaling limit by 2028, further scaling will be enabled by 3D fabrication. This, however, will not improve the energy efficiency [1]. Novel applications, such as, Internet-of-Things (IoT), look-up memory, wearable devices, and neuromorphic computing, calls for research and development of ultra-low-power nanoscale devices. Researchers are exploring several emerging technologies that can augment or replace CMOS in these energy-constrained applications. All these emerging memory devices, such as, resistive memory (ReRAM), phase change memory (PCRAM), magnetoresistive memory (MRAM), and ferroelectric field effect transistors (FeFET) demonstrate some degree of non-volatility, a property which enables data retention in the absence of a power supply [2]. However, most of these devices suffer from their limited contrast in resistance between the ON and OFF states (ON-OFF ratio). High OFF current leads to high leakage, resulting in greater static power consumption [3].

The Phase Change Nanoelectromechanical Relay (PCNR) is one such emerging technology, which is very suitable for the aforementioned applications as it combines the nonvolatility of phase change materials (PCM) and the high ON-OFF current ratio (10^8) of nanoelectromechanical (NEM) relay architectures. Different from all previously demonstrated relays, the PCNR is highly scalable [4]. PCNR utilizes the 10% reversible volume expansion of

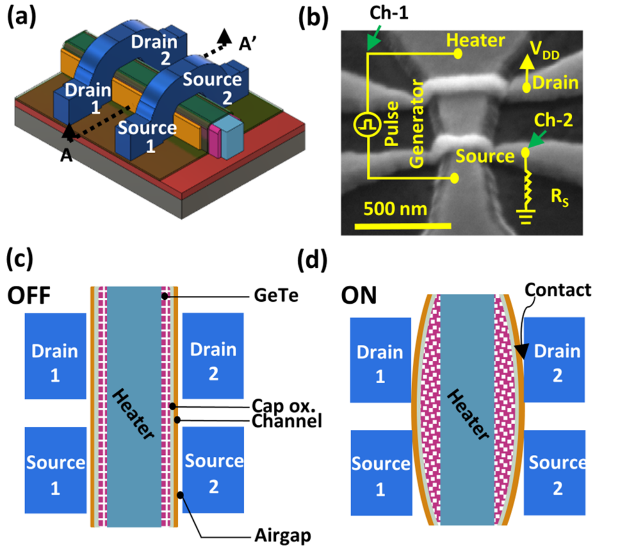

Figure 1:(a) Schematic model of a 4-terminal FinPCNR device. (b)SEM image of a fabricated device with schematic test setup. (c-d) A-A' horizontal cross-section of the device in the as fabricated OFF and ON states, respectively. The lateral actuator connects Drain 1 (2) and Source 1(2) through the left (right) side channel. The electrodes of each side are connected, as shown in (a), to reduce contact resistance.

GeTe to open and close a pair of metal contacts [5]. Microscale vertically actuating PCNR devices have been reported to have very low actuation voltage (1.1 V) and very high ON-OFF current ratio (10^8) due to its 20 nm airgap [6]. Here we present an advanced scaled down design of PCNR – the FinPCNR. This fin-shaped laterally actuating relay turns on with a sub-300 mV actuation pulse. Sub-5 nm airgap successfully maintains the desired low leakage during operation. While the prototype FinPCNR already occupies an area (300 nm x 100 nm) smaller than any other NEM relay design, there is plenty of room left for further scaling as this architecture does not require any anchored flexure.

OPERATING PRINCIPLE

Fig. 1 shows a schematic diagram of the FinPCNR, illustrating its (a) 3D structure, (b) SEM image with a schematic test setup and horizontal cross-sections in the (c) OFF and (d) ON states. Voltage is applied across the heater using a pulse generator. Heater voltage and channel current are recorded using the ch-1 and ch-2 oscilloscope probes, respectively. The FinPCNR comprises of two main components- the contact pair and the lateral actuator. The contact pair is formed by a pair of Pt drain and source electrodes, and a Pt channel placed on the sidewall of the actuator. The metal channel bridges the drain and source electrodes when the relay is in the ON state. The actuator consists of a tungsten heater, a sidewall layer of GeTe, and a thin layer of Al_2O_3 to encapsulate GeTe during phase

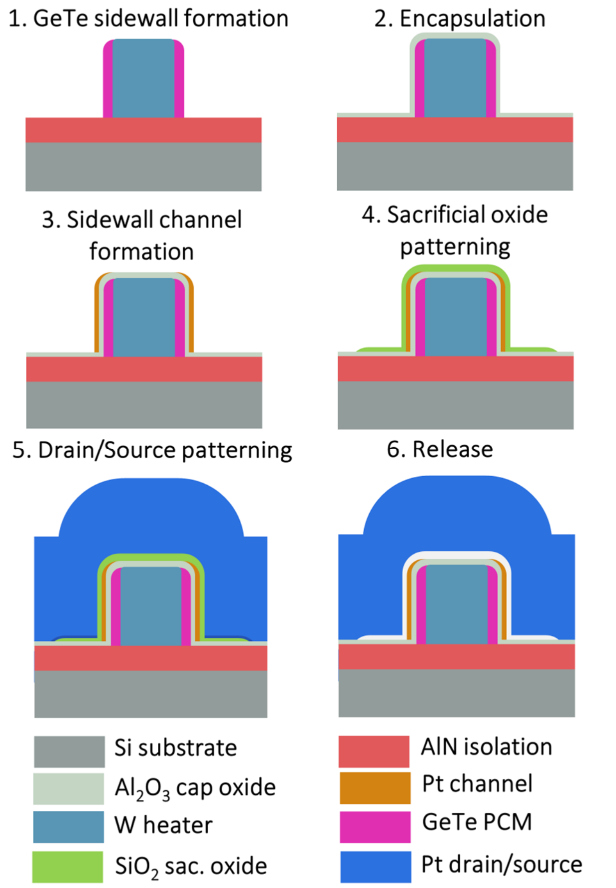

Figure 2: Sidewall formation steps around the heater mandrel. Preliminary steps of AlN deposition and heater mandrel formation are not shown.

change. Transformation of GeTe between the crystalline (smaller) and amorphous (larger) states results in lateral expansion and contraction of the actuator. We use GeTe as the PCM as its volume changes by 10% during phase transformation. It is also capable of retaining its state at higher temperature than other widely used phase change materials, such as $Ge_2Sb_2Te_5$ (GST) [7].

As fabricated, GeTe is in the low volume crystalline state. The thickness of the sacrificial material determines the size of the gap after release. The gap is sized to ensure that the expected volume change in GeTe layer is sufficient to make contact between the electrodes and the channel. We apply an electric pulse on the heater to raise the temperature of GeTe over its melting point (T_{melt}^{GeTe}=1000K). Molten GeTe is quickly quenched into the amorphous state. The expanded layer of GeTe presses the metallic channel into the drain and source, forming a contacting bridge between the two electrodes. A similar process returns the FinPCNR to the OFF state. This increases the PCM temperature above its glass transition point (500 K for GeTe) and rapidly crystallizes any amorphous portion of the film. Unlike the switching ON process, the PCM does not need to be melted this time. As a result, the relay can be switched back at a lower voltage. However, an input pulse with a slow trailing edge is preferred for RESET as it ensures complete recrystallization of the PCM. At the end of this pulse, the crystalline PCM contracts and separates the metallic

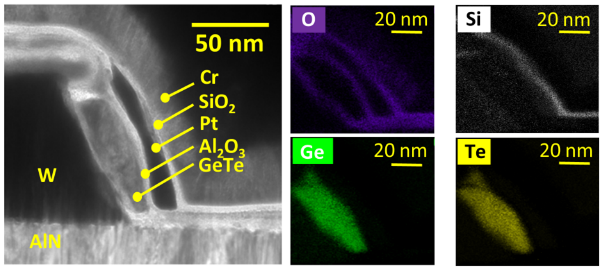

Figure 3:Cross-sectional TEM image of a device before release. EDX element map from STEM-HAADF shows the regions with GeTe and sacrificial SiO2.

channel from the drain and source, once again creating an airgap and turning the relay OFF. The switch ON and OFF pulses can also be called actuation and recrystallization pulse, respectively.

FABRICATION PROCESS

The fabrication process involves multiple self-aligned sidewall formation steps around the heater mandrel. These self-aligned processes prevent misalignment from conventional patterning with electron-beam lithography (EBL). At first, 100 nm AlN is deposited on a Si substrate. This layer provides electrical insulation but good thermal conductivity between the heater and the substrate. Next, 100 nm tungsten is deposited and patterned with SF_6 plasma in a reactive ion etching (RIE) tool to produce sub-100 nm wide heaters. The high aspect ratio heater acts as

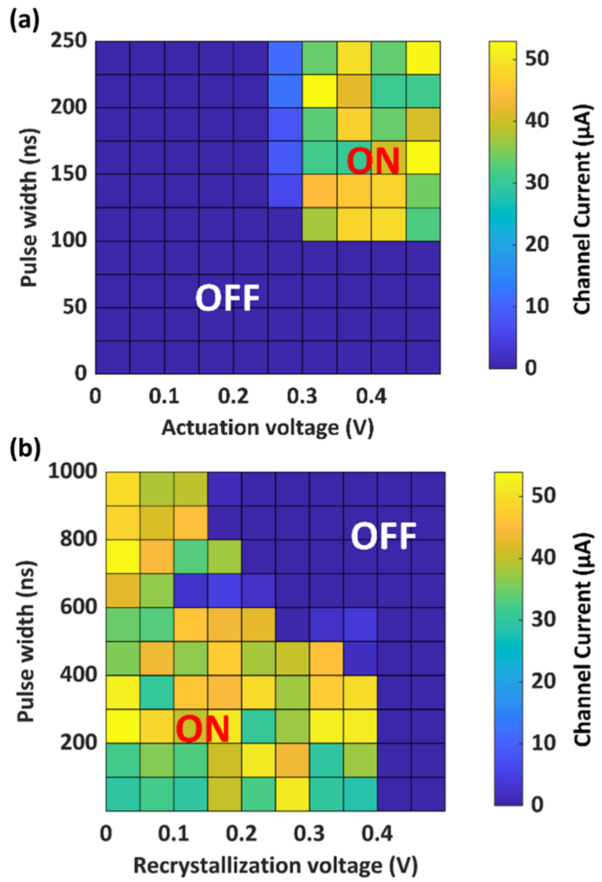

Figure 4: Channel current measured after applying a wide range of pulse amplitude and duration for (a) actuation and (b) recrystallization.

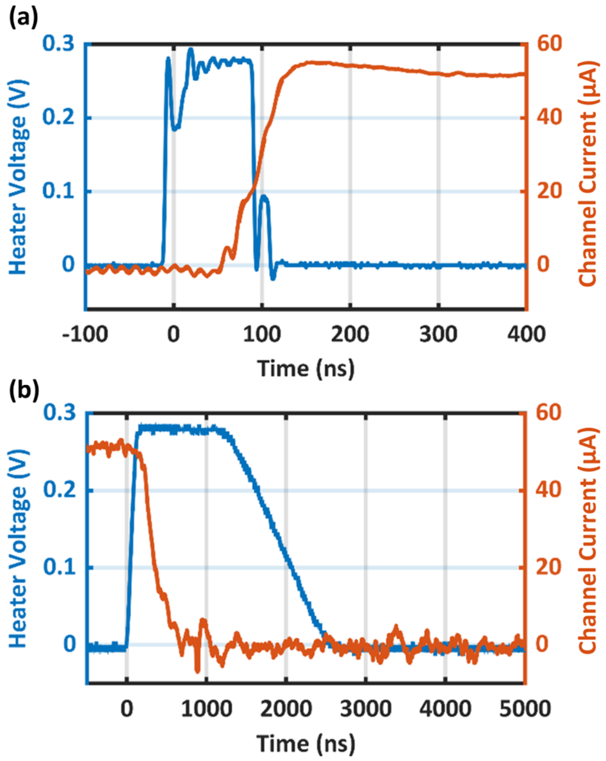

Figure 5: Heater voltage and resulting change in channel current during (a) actuation and (b) recrystallization.

the mandrel for the following self-aligned sidewall patterning steps. In the next step, 30 nm GeTe (PCM) is deposited in a co-sputtering tool that ensures semi-conformal deposition with the help of a rotating chuck. The substrate is heated at 220^0C to crystallize the PCM film. Then it is etched with Ar^+ plasma in an inductively coupled plasma (ICP) RIE tool. The etch process is precisely timed so that only the sidewall PCM survives. We use cross-sectional TEM as well as electrical testing to determine the exact sidewall etch time. Next, a layer of 5 nm alumina is deposited in the ALD tool as an encapsulation layer. This alumina layer is crucial as it contains the molten GeTe during phase transformation. This deposition is done at a high temperature (250^0C) to reduce the number of pinholes in the alumina film. Next, 10 nm ALD Pt is deposited as the channel material. This layer is etched using Ar^+ plasma in an ion-milling tool for effective sidewall metallization [8]. Next, 3~5 nm sacrificial oxide is deposited to separate the actuator stack from the following layer of electrodes (drain and source). Finally, 100 nm thick metal (Pt with a Cr adhesion layer) is patterned to form the electrodes. Fig. 3 illustrates all layers before the release step in a cross-sectional TEM image. EDX results clearly demonstrate a thin SiO_2 layer between the metal contacts. As a final step, the sacrificial oxide is selectively etched using vapor HF to release the device and form the desired airgap.

DEVICE CHARACTERIZATION

A wide range of input voltages and pulse duration (width) are tested to find the most suitable combination of amplitude and duration for both actuation and recrystallization voltages, as depicted in Fig. 4. Actuation pulses have fast rising and falling time (2 ns) to facilitate the melt-quench cycle. Recrystallization pulses have slow falling edge (up to 1 µs) to ensure that complete recrystallization is achieved at every cycle. The OFF state channel current is measured (23 fA) with a B1500 parameter analyzer.

Fig. 5 shows the dynamic change in channel current in response to applied pulses. The RC delay is caused by the current limiting resistor connected to the source electrode. 100 ns wide 290 mV actuation pulse switches the relay ON. A recrystallization pulse of the same amplitude but longer duration, with 100 ns rising and 1 µs falling edge is applied to turn it OFF. It is evident that the contacts are opened within the first 100 ns of the onset of the pulse.

Operating voltage in the reported device dimensions is already compatible with CMOS power supplies. Faster switching and further voltage scaling should be expected from smaller device dimensions.

CONCLUSIONS

This paper reports the first demonstration of a highly scalable nonvolatile NEM relay with <5 nm air-gap. A very low actuation voltage makes it an ideal candidate for high-density nonvolatile memory operation. This vertical structure of Fin PCNR paves the way for further scaling and the development of more reliable emerging non-volatile and low-leakage memory architectures.

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