Extended Abstract—Patterning surfaces leads to the creation of physiochemical heterogeneities (i.e. surface energy, chemical reactivity, conductivity, topography, etc) which are important to the design of complex components used in modern electronics. The ability to control patterns and write and rewrite circuits is critical for adaptive learning in future electronic devices.

Brain-inspired computing is an emergent field which aims to extend the capabilities of information technology beyond digital logic. Compact nanoscale devices, mimicking biological synapses are needed as the building blocks of brain-like adaptive computation. The brain, a far more efficient tool for computation when compared to tradition electronic devices, requires 6 to 9 orders of magnitude less energy to comparable super computer computation. The human brain consists of ~10^{11} neurons and an extremely large number of synapses ~10^{15} which act as complex interconnected bridges among neurons. Therefore, a nanoelectronic device that can emulate the plasticity of synaptic pathways, with diverse electrical connections being built or broken over time, is one of the most important tools for creating brain inspired computations systems. Utilizing phase change materials in novel 3D geometry may be a promising method to achieve such low energy adaptive circuits, relying on nanoscale electrical changes to build potentially rewritable conductive pathways.

Phase change materials exhibit a unique switching behavior between high resistivity to low resistivity states depending on induced crystallographic changes. For the case of chalcogenide glasses, this occurs through the transition from amorphous to crystalline which can be controlled either by electric field pulsing (Ovshinsky effect) or heating above the crystallization temperature. Since the discovery of chalcogenide-based phase change materials, significant research has been performed to improve the understanding of the phase transition, reduce power consumption for transition and enhance cycle endurance through researching material-specific properties and growth routes. The most common applications of chalcogenide phase change materials are seen in rewritable CD memory, where the different states of the material have different optical properties allowing for storage, and electronic phase-change memory, where the varying electrical conductance of different states enables data retention. In this work, we report on the nanopatterning of GeTe-based films using heated atomic force microscope (AFM) tips to create local regions of conductive, crystalline material in an insulating, amorphous base film. Localized patterning of arbitrary conductive connections and the ability to perform this task in-situ using heated nanoscale AFM tips represent a first-step in the demonstration of rewritable phase-change-material-based circuits.

GeTe Thin film samples of approximately 1 micron thick were prepared using a magnetron RF sputtering system and a stoichiometric binary target. Due to the differing sputtering rates of the components elements, stoichiometry was approximately 70/30 Te:Ge as measured by Rietveld refinement on crystallized samples and wavelength dispersive x-ray spectroscopy on both the crystalline and amorphous films. Films were deposited at 100W onto insulating and conductive Si wafers at room temperature. Wafers were chosen depending on the need of electrical studies. As-deposited films were amorphous as verified by X-ray diffraction. The resistivity of the GeTe film was measured as a function of temperature, with the initially insulating amorphous GeTe demonstrating a two-stage reduction in resistance as the film was crystallized, with dramatic drops in resistance observed at approximately 210°C and 230°C. The multiple steps may be the result of the non-stoichiometry of the film and additional experiments are planned to further characterize the nature of the phase transition.

Using heated AFM tips to induce the amorphous-crystallization (insulator-conductor) transition in specific locations on the film, electronic patterns with distinct topography and conductivity were written and characterized, paying specific attention to the impact of varying tip temperature and write speed on pattern fidelity. Figure 1(a) shows an AFM image of four crystalline lines written via a heated-tip at different tip speeds. Associated with the crystalline phase transition is a large volumetric change as the atoms reorder from the loosely packed amorphous state to the densely packed crystalline state. As a result, the crystalline regions appear as depressions in the AFM topographic scan. A depth profile of the written area as a function of tip speed is shown in Figure 1(b), indicating that pattern depth can be controlled and varied by appropriate choice of tip velocity. The width of the channels could be varied from 300 nm to 450nm, with depths reaching approximately 80 to 100nm. Such nanoscale topographic changes may also be of significant interest to lab-on-chip applications where minute grooved channels are needed, with the added benefit of being electrically conducting for added sensing capability.

In order to determine the volume of the crystallized, and thus conductive region, cross-section transmission
electron microscopy (TEM) images of the area were acquired. Cross-sections were obtained using focused ion beam (FIB) preparation and both bright- and dark-field TEM images were examined to characterize the subsurface material modifications induced by patterning. The crystallized region for various written patterns can clearly be seen in the TEM of Figure 2. It is observed that there exists a small region of crystallinity which again depends on the temperature and speed of the writing process, with higher tip temperatures and slower writing speeds resulting in larger crystallized volumes. The thin dark area below the indentation is an artifact of the FIB preparation process (“curtaining”). The rest of the film remains unchanged and amorphous.

As the crystallized regions are electrically conductive while the amorphous material remains insulating, the patterned areas of our GeTe films demonstrate a change in surface potential. Kelvin probe force microscopy (KPFM) measurements (not shown) on a series of lines written at constant tip temperature (estimated at approximately 230°C at the film surface) and varying writing speed indicate a potential difference between the patterned lines and surrounding amorphous material of 32mV to 70mV, indicating the dependence of the degree of crystallization on writing speed. The physical properties and mechanism for localized crystallization will be discussed in detail.

**Topic — Nanoelectronics; Nanofabrication; Emerging material and device challenges in futuristic nanoelectronics**

**Index Terms/Keywords —** Phase Change Materials, GeTe, chalcogenides, FIB, AFM, TEM, amorphous, PCM

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**REFERENCES**