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January 23, 2020

Defense Technical Information Center
Office of Naval Research
8725 John J Kingman Road Ste 0944
Fort Belvoir VA 22060-6218

RE: Final Technical Report with SF298 for Grant Number N000141512395

Dear Defense Technical information Center:

Attached please find the final technical report for Grant Number N000141512395, "Ohmic Contacts to Phase Change Materials for RF Switches", with Prof. Suzanne E. Mohney as the PI.

Yours truly,

Suzanne Mohney

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14. ABSTRACT
Researchers at The Pennsylvania State University investigated ohmic contacts to the phase change material germanium telluride and gained a fundamental understanding of ohmic contacts for radio frequency switches fabricated from germanium telluride. Using x-ray photoelectron spectroscopy, they examined pre-metallization surface preparations of germanium telluride, and they studied how the resulting germanium-to-tellurium ratio and effectiveness of removal of the native oxide affected contact resistance. They also surveyed reactivity of germanium telluride with metals across the periodic table using transmission electron microscopy of thin-film samples and thermodynamic calculations. An unexpected trend in contact resistance with the work function of the first metal layer in the metallization stack was explained by understanding the effect of interfacial reactions with germanium telluride. Molybdenum as the first layer in an ohmic contact stack resulted in contact resistances near 0.004 Ohm-mm (5×10^{-9} Ohm-cm^2) when an *in situ* Ar+ ion pre-metallization surface treatment was used. A tin-based contact also provided very low contact resistance, permitting an *ex situ* surface treatment but requiring annealing. Its low resistance was ascribed in part to the formation of tin telluride.

15. SUBJECT TERMS
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Final Technical Report

Ohmic Contacts to Phase Change Materials for RF Switches

PI: Suzanne Mohney
The Pennsylvania State University

ONR Award N00014-15-1-2395
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1. Abstract (also appears on SF 298):

Researchers at The Pennsylvania State University investigated ohmic contacts to the phase change material germanium telluride and gained a fundamental understanding of ohmic contacts for radio frequency switches fabricated from germanium telluride. Using x-ray photoelectron spectroscopy, they examined pre-metallization surface preparations of germanium telluride, and they studied how the resulting germanium-to-tellurium ratio and effectiveness of removal of the native oxide affected contact resistance. They also surveyed reactivity of germanium telluride with metals across the periodic table using transmission electron microscopy of thin-film samples and thermodynamic calculations. An unexpected trend in contact resistance with the work function of the first metal layer in the metallization stack was explained by understanding the effect of interfacial reactions with germanium telluride. Molybdenum as the first layer in an ohmic contact stack resulted in contact resistances near 0.004 Ω•mm (5 x 10^{-9} Ω•cm^2) when an *in situ* Ar+ ion pre-metallization surface treatment was used. A tin-based contact also provided very low contact resistance, permitting an *ex situ* surface treatment but requiring annealing. Its low resistance was ascribed in part to the formation of tin telluride.

2. Objectives

Metal ohmic contacts can contribute 20–50% of the on-state resistance of radio frequency (RF) switches fabricated from the phase change material GeTe. Moreover, switches are turned on and off through heating, necessitating an understanding of reactions between metals and GeTe at elevated temperatures. Therefore, researchers at The Pennsylvania State University proposed the following research objectives:

- Develop a fundamental understanding of electrical contacts to GeTe and related materials,
- Examine pre-metallization surface preparation and interfacial reactions that occur between contact metals and GeTe during annealing,
- Engineer the Schottky barrier height and/or reduce contact resistances by tailoring the surface composition of GeTe through alloying
- Use insights gained to engineer ohmic contacts with reduced resistance, while maintaining excellent thermal stability, and
- Develop ohmic contacts with specific contact resistances ≤ 5 x 10^{-9} Ω•cm^2 and high reliability suitable for RF phase change switches.

3. Accomplishments/New Findings

3.1 Treatment of the Surface of Germanium Telluride

In general, both interfacial contaminants and the surface stoichiometry of a compound can greatly affect current transport through the interface between the compound and a metal contact. At the outset of our study, we therefore investigated the effect of wet and dry treatments on the composition of the surface of GeTe thin films using x-ray photoelectron spectroscopy (XPS). We also studied how the treatments affected the resistance of ohmic contacts to GeTe.[1]

In Table 1 we compare 5 surface treatments, all of which followed degreasing for 5 min in acetone, 5 min in isopropyl alcohol, rinsing for 15 s in deionized (DI) H_2O, and blowing dry with N_2 gas. While *in situ* treatment with Ar^+ ions most effectively removed the native oxide on GeTe, it also left the surface rich in Ge due to preferential sputtering of Te. *Ex situ* treatment with deionized H_2O was surprisingly effective at removing most of the oxide on GeTe after GeTe had been treated with UV-ozone. On the other hand, more GeO_2 was observed after we attempted to passivate the surface of GeTe using an $(NH_4)_2S$ solution. The HCl treatment created the most Te-rich surface.

Table 1. *Treatments and their effect on the surface of GeTe according to XPS. This table summarizes findings reported in Ref. 1.*

Treatment	Steps	Notes from XPS
UV-ozone	Degrease 10 min in UV-ozone	Mostly GeO_x and TeO_y Little GeO_2 and TeO_2
Ar^+ etching	Degrease 5 min Ar^+ ion etching	Ge-rich surface No oxide detected
H_2O	Degrease 10 min in UV-ozone 5 min DI H_2O rinse Blow dry with N_2 gas	Little but detectable GeO_x
HCl	Degrease 10 min in UV-ozone 2 min 1:10 HCl:DI H_2O 15 s DI H_2O rinse Blow dry with N_2 gas	Te-rich surface Little but detectable GeO_x
$[NH_4]_2S$	Degrease 10 min in UV-ozone 30 s 1:100 $(NH_4)_2S$:DI H_2O 15 s DI H_2O rinse Blow dry with N_2 gas	GeO_2 detected

For some metallization schemes, the surface treatments clearly altered the contact resistance. For example, for Mo-based contacts, an *in situ* Ar^+ ion treatment helped reduce the contact resistance to a very low value.[2] On the other hand, the HCl treatment increased the resistance of Ni-based contacts, as shown in Fig. 1.[1] We correlated this observation to the formation of a nickel telluride, as identified by transmission electron microscopy (TEM), from reaction of Ni with elemental Te remaining on GeTe after treatment with HCl.

1. Aldosari, Haila M.; Simchi, Hamed; Ding, Zelong; Cooley, Kayla A.; Yu, Shih-Ying; Mohney, Suzanne E., *ACS Appl. Mater. Inter.* **8** 34802 (2016)
2. Aldosari, Haila M.; Cooley, Kayla A.; Yu, Shih-Ying; Simchi, Hamed; and Mohney, Suzanne E., *J. Appl. Phys.* **122** 175302 (2017)

3.2 Test Structures

We used transmission line model/transfer length method (TLM) test structures with probe pads at the sides of the front of the contacts to measure very low contact resistances and specific contact resistances in this work. Gaps were 0.6–20 μm between pairs of contacts, with feature sizes measured by scanning electron microscopy.[3] We checked[4] if we could use circular[5] or multi-ring circular[6] TLM test structures, but our measurements were too sensitive to the metal sheet resistance to extract correct values of contact resistance using the otherwise convenient circular test structures.

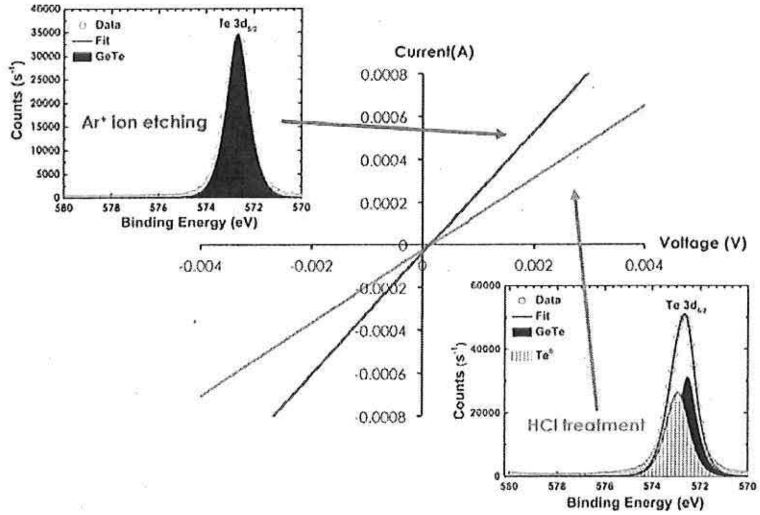

Figure 1. *Treatment of the GeTe surface with HCl leaves the surface rich in Te, and reaction of elemental Te with Ni leads to lower current or higher contact resistance. (Reprinted with permission from Ref. 3. Copyright 2018 American Chemical Society.)*

3.3 Contact Resistance of Different Metallizations

We systematically studied different metallization schemes for ohmic contacts to GeTe. We prepared these contacts on polycrystalline GeTe films that were 110 nm thick with a sheet resistance ~40 Ω/square on SiN_x/Si. Table 2 summarizes our data. Although it is not difficult to make an ohmic contact to GeTe, which is a degenerate *p*-type semiconductor, an extremely low contact resistance is needed to avoid the impact of a parasitic resistance in RF switches in the on state. We targeted contact resistances < 0.005 Ω•mm.

The contacts with the lowest resistance in our study were (1) Mo/Ti/Pt/Au prepared with *in situ* Ar^+ ion etching prior to metallization[7] and (2) Sn/Fe/Au prepared with an *ex situ* pre-metallization treatment in DI water and annealed for 30 min at 200 °C.[8] No interfacial reaction was observed between Mo and GeTe using TEM, and annealing was not necessary (or desirable) for achieving a minimum R_c of 0.003–0.004 Ω•mm (~5 x 10^{-9} Ω•cm^2). The low R_c of our Sn-based

3. Aldosari, Haila M.; Simchi, Hamed; Ding, Zelong; Cooley, Kayla A.; Yu, Shih-Ying; Mohney, Suzanne E., *ACS Appl. Mater. Inter.* **8** 34802 (2016)
4. Aldosari, Haila M., Ph.D. Thesis, The Pennsylvania State University (2016)
5. Marlow, Gregory S. and Das, Mukunda B., *Solid-State Electron.* **25** 91 (1982)
6. Yu, Hao; Schaekers, Marc; Schram, Tom; Rosseel, Erik; Martens, Koen; Demuynck, Steven; Horiguchi, Naoto; Barla, Kathy; Collaert, Nadine; De Meyer, Kristin; and Thean, Aaron, *IEEE Electron. Device Lett.* **36** *600* (2015)
7. Aldosari, Haila M.; Cooley, Kayla A.; Yu, Shih-Ying; Simchi, Hamed; and Mohney, Suzanne E., *J. Appl. Phys.* **122** 175302 (2017)
8. Simchi, Hamed; Cooley, Kayla A.; Ding, Zelong; Molina, Alex; and Mohney, Suzanne E., *ACS Appl. Mater. Inter.* **10** 16623 (2018)

contacts (also ~0.004 Ω•mm) was attributed in part to formation of narrow-gap SnTe at the contact interface. We were also able to achieve low R_c values with Au contacts.[9]

Table 2. *Contact resistance (R_c), specific contact resistance (ρ_c), and corresponding sheet resistance of GeTe (R_{sh}) for each metallization scheme, pre-metallization surface treatment, and annealing condition (if any) resulting in the reported minimum R_c. AD = as deposited.*

Contact Metal	R_c (Ω.mm)	ρ_c (Ω.cm^2)	R_{sh} (Ω.□$^{-1}$)	Surface Treatment	Annealing Condition	Ref.
Ti/Pt/Au	0.010	2.6×10^{-8}	42	H_2O, HCl	AD	10
Ni/Ti/Pt/Au	0.016	6.4×10^{-8}	40	Ar^+ plasma, H_2C $(NH_4)_2S$	AD	11
Au	0.007	1.2×10^{-8}	43	Ar^+ plasma H_2O, HCl $(NH_4)_2S$	AD	10
Au	0.0045	6×10^{-9}	39	H_2O	AD	--
Mo/Ti/Pt/Au	0.0033	5×10^{-9}	37	Ar^+ plasma	AD	12
Sn/Fe/Au	0.0037	5×10^{-9}	43	H_2O	200 °C	10
Cr/Pt/Au	0.0055	9.6×10^{-9}	36	HCl	AD	--
Pt/Ti/Au	0.036	3.6×10^{-7}	42	Ar^+ plasma	AD	--

Considering the *p*-type conductivity of GeTe, we would predict from the Schottky-Mott model that a metal with a high work function would give the lowest Schottky barrier between the metal and GeTe and therefore lowest contact resistance in the absence of Fermi level pinning. If there were complete Fermi level pinning, we would expect little dependence on the metal work function. Instead, Fig. 2 shows the opposite trend: When metals with the highest work functions (Pt and Ni) were the first layer in the stack deposited, the result was clearly a higher contact resistance! Pt-based contacts exhibited a resistance of 0.036 Ω•mm, while Ni-based contacts offered a resistance of 0.016 Ω•mm. The explanation for this unexpected trend comes from our study of interfacial reactions.

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9. Aldosari, Haila M.; Cooley, Kayla A.; Yu, Shih-Ying; Kragh-Buetow, Katherine C.; Mohney, Suzanne E., *Thin Solid Films* **621** 145 (2017)
10. Simchi, Hamed; Cooley, Kayla A.; Ding, Zelong; Molina, Alex; and Mohney, Suzanne E., *ACS Appl. Mater. Inter.* **10** 16623 (2018)
11. Aldosari, Haila M.; Simchi, Hamed; Ding, Zelong; Cooley, Kayla A.; Yu, Shih-Ying; Mohney, Suzanne E., *ACS Appl. Mater. Inter.* **8** 34802 (2016)
12. Aldosari, Haila M.; Cooley, Kayla A.; Yu, Shih-Ying; Simchi, Hamed; and Mohney, Suzanne E., *J. Appl. Phys.* **122** 175302 (2017)

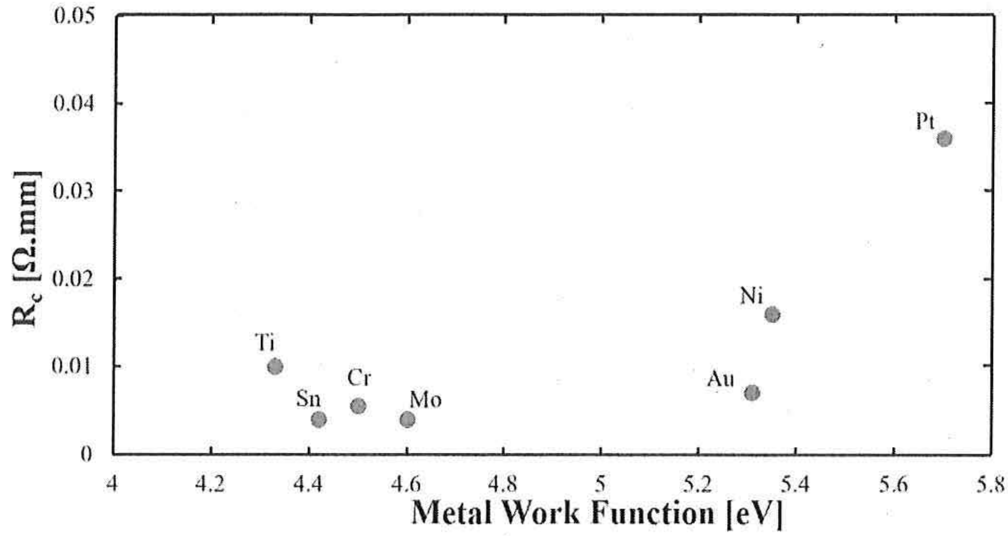

Figure 2. *Contact resistance as a function of metal work function.*

3.4 Interfacial Reactions and Their Impact on Contact Resistance

It is clear that interfacial reactions occur between some metal contacts and GeTe based on transmission electron microscopy, even with no more thermal treatment than required to pattern devices by photolithography. For example, we observed $Ni_{1.29}Te$ when Ni was deposited on HCl-treated GeTe,[13] which is Te-rich. We correlated the formation of $Ni_{1.29}Te$ with a high contact resistance (0.036 Ω•mm). We measured a contact resistance of 0.016 Ω•mm, which was still high relative to other metal contacts we studied, when we used more favorable surface preparations (Ar^+ ion cleaning or UV-ozone/DI water). Upon annealing the Ni-based contacts at 200 °C, both nickel germanides and nickel tellurides formed, and the contact resistance increased.

Based on thermodynamic calculations,[14] we found a similar driving force for reaction between Pt and GeTe. Likewise, we observed a very high resistance of 0.036 Ω•mm for Pt/Ti/Au contacts deposited on GeTe that had been cleaned *in situ* with Ar^+ ions. Upon annealing at 200 °C, reaction into the gap between the contacts occurred, making further measurements of contact resistance inaccurate.

We studied Ti/Pt/Au contacts because this metallization stack is used as an ohmic contacts on many semiconductors. We measured a contact resistance of 0.010 Ω•mm (3 x 10^{-8} Ω•cm^2), which increased from 0.012 Ω•mm upon annealing for 30 min at 200 °C.[15] This contact did not offer as low of a resistance as Mo/Ti/Pt/Au, Au, or annealed Sn/Fe/Au, which we discuss in more detail below. Moreover, its thermal stability was poorer. However, the reaction between Ti and GeTe was confined to a thin interfacial layer according to TEM without significant reaction into the gap

13. Aldosari, Haila M.; Simchi, Hamed; Ding, Zelong; Cooley, Kayla A.; Yu, Shih-Ying; Mohney, Suzanne E., *ACS Appl. Mater. Inter.* **8** 34802 (2016)
14. Cooley, Kayla A. and Mohney, Suzanne E., *J. Vac. Sci. Technol. A* **37** 061510 (2019)
15. Simchi, Hamed; Cooley, Kayla A.; Ding, Zelong; Molina, Alex; and Mohney, Suzanne E., *ACS Appl. Mater. Inter.* **10** 16623 (2018)

between the contacts. Interfacial reaction products were 3 nm and 13 nm thick, respectively, upon deposition or after annealing for 12 h at 200 °C. Both $TiTe_2$ and elemental Ge were detected by electron diffraction after annealing. Formation of $TiTe_2$ and elemental Ge is consistent with the Ti-Ge-Te phase diagram we predicted from classical thermodynamics.[16]

Cr/Pt/Au offered a low resistance of 0.055 Ω•mm upon deposition, but like the Ti/Pt/Au contacts, their resistance increased upon annealing for 30 min at 200 °C (in this case to 0.007 Ω•mm), likely again due to reaction of Cr with GeTe.

We selected Sn as the first layer of a stack metallization in another set of experiments[17] in an effort to form SnTe, which has a lower bandgap (0.2 eV) than GeTe (0.7 eV). We suspected that this approach might reduce any barrier at the metal/GeTe interface and also reduce the contact resistance. A contact stack of Sn/Fe/Au was employed with Au as a cap to provide a low sheet resistance. Iron was chosen a diffusion barrier because Fe was previously reported to be thermally stable against reaction with SnTe. As-deposited Sn/Fe/Au contacts provided very low contact resistance (0.0055 Ω•mm). Their resistance decreased further to 0.004 Ω•mm after an anneal at 200 °C for 30 min. Transmission electron microscopy (TEM) was used to examine the interface of the contact, confirming that SnTe was indeed present. The contact resistance was sensitive to the choice of barrier between the Sn and Au (e.g., Mo instead of Fe led to a high resistance), and we suspected that diffusional doping of GeTe by Fe might be a contributing factor to the low contact resistance.

For Au contacts, the lowest values of contact resistance were for the as-deposited case (0.0045–0.007 Ω•mm). For contacts with an initial contact resistance of 0.007 Ω•mm,[18] the resistance increased by ~30% and 90% after 30 min at 250 °C and 350 °C, respectively. We found from TEM that there was no new reaction product formed at the interface between Au and GeTe after annealing; however, Te escaped through thin slits that appeared in the Au film, as shown in Fig. 3. Loss of Te was correlated with localized voids at the GeTe/SiN_x interface, and we suspect that loss of Te may also have led to slight changes in the stoichiometry of GeTe during annealing. Since Ge vacancies are acceptors in GeTe, a shift towards a more Ge-rich composition would result in a higher contact resistance.

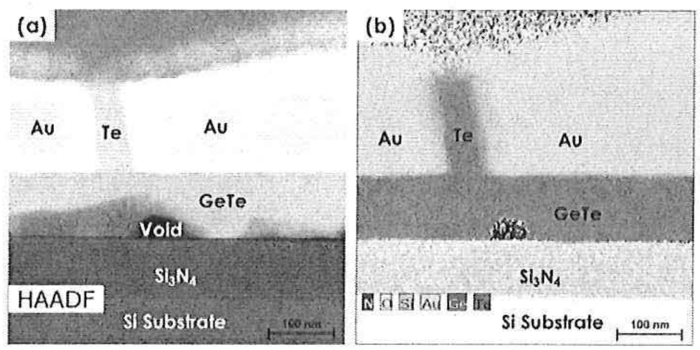

Figure 3. *Gold contacts to GeTe annealed at 350 °C for 30 min and capped with 10 nm of SiO_2: (a) high-angle annular dark field scanning transmission electron microscopy image and (b) energy dispersive spectroscopy map (Reprinted with permission from Ref. 18. Copyright 2017 American Chemical Society.)*

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16. Cooley, Kayla A. and Mohney, Suzanne E., *J. Vac. Sci. Technol. A* **37** 061510 (2019)
17. Simchi, Hamed; Cooley, Kayla A.; Ding, Zelong; Molina, Alex; and Mohney, Suzanne E., *ACS Appl. Mater. Inter.* **10** 16623 (2018)
18. Aldosari, Haila M.; Cooley, Kayla A.; Yu, Shih-Ying; Kragh-Buetow, Katherine C.; Mohney, Suzanne E., *Thin Solid Films* **621** 145 (2017)

For Mo/Ti/Pt/Au contacts, which had very low resistance, we again found no solid-state reaction product at the Mo/GeTe interface upon deposition or after annealing. The contact resistance did not change after annealing for 30 min at 200 °C, but after a week, it almost quadrupled from 0.003 Ω•mm to 0.011 Ω•mm.[19] Such an increase in resistance would be serious for an RF switch and corresponded to migration of Te. In this case, the Te appeared in the Ti/Pt/Au cap in the form of a platinum telluride, as shown in Fig. 4. Since no Ge-bearing reaction product could be found, we concluded that the stoichiometry of the GeTe film must have shifted. Loss of Te from GeTe would lead to a reduction in Ge vacancies, which are acceptors in GeTe, resulting in a higher contact resistance. To further improve the Mo-based contacts, we should avoid including the Pt layer that reacts with Te.

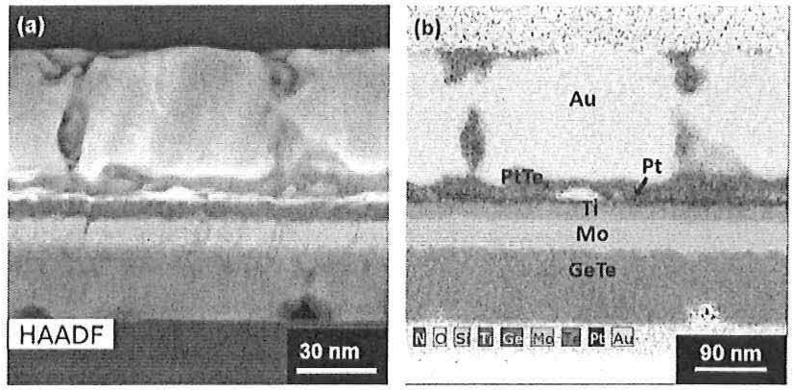

Figure 4. *(a) High angle annular dark field scanning transmission electron microscopy and (b) energy dispersive spectroscopy map of Mo/Ti/Pt/Au contacts to GeTe aged for 1 week at 200 °C. Reproduced from Ref. 19 with the permission of AIP Publishing.*

With only one exception (the Sn/Fe/Au contacts in which SnTe formed), we observed that reactivity with the contact metal was detrimental to forming a low resistance ohmic contact to GeTe. In some cases, the effect was great: Ni/Ti/Pt/Au and Pt/Ti/Au contacts were very reactive and offered the highest contact resistance. This effect was linked to the high reactivity of the first-layer metallization (Ni or Pt) with GeTe. In other contacts, detrimental reactions were less extensive or required more severe annealing conditions to occur. In Ti/Pt/Au contacts, reactions were confined to a thin layer of reaction products (Ti/Pt/Au) after annealing for 30 min at 200 °C. Even contact metals that were otherwise unreactive (such as Au) were still prone to loss of Te due to volatilization, or Te migrated to the Pt layer in a Ti/Pt/Au cap above unreactive Mo contacts. Overall, Mo contacts appear to be particularly promising among all the contacts tested, since they offer a particularly low contact resistance as prepared and good thermal stability. With the exchange of a Ti/Pt/Au cap for another metallization during integration, Mo could be the most thermally stable solution for very low resistance ohmic contacts to GeTe that can undergo repeated thermal cycling in an RF switch.

3.5 Metal-Ge-Te Phase Equilibria and Metal/GeTe Reactivity Across the Periodic Table

We evaluated the reactivity of GeTe at 200 °C with many metals not mentioned earlier in the report using transmission electron microscopy. We also gathered phase diagrams and used thermodynamics to predict room-temperature ternary phase equilibria in other metal-Ge-Te systems. In addition to our interest in low-resistance thermally stable contacts, we were motivated by the

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19. Aldosari, Haila M.; Cooley, Kayla A.; Yu, Shih-Ying; Simchi, Hamed; and Mohney, Suzanne E., *J. Appl. Phys.* **122** 175302 (2017)

potential to (1) engineer the crystallization speed, power consumption, and endurance of phase change material devices, (2) modify the Seebeck coefficient and conductivity of phase change materials, and (3) create dilute magnetic materials for spintronics through alloying with transition metals.[20]

Our survey[20] revealed that Au and Zn thin films are in thermodynamic equilibrium with GeTe at room temperature or the mildly elevated temperatures at contact interfaces in remotely heated RF phase change switches. Therefore, we did not observe Au and do not expect Zn to be reactive with GeTe in a closed system (encapsulated). Other metals are also unreactive at 200 °C, but probably due to kinetic limitations. From our experimental work, such unreactive metals include Mo, Ru, and Re; the literature review places W and Ta in the same category. We experimentally observed reactions of Ag, Al, Cu, Fe, Mn, Pd, Ni and Ti films on GeTe. We also report thermodynamic driving forces for reaction of GeTe with Cd, Co, Hf, Pt, Rh, Sc and Y.

Interestingly, we observed solubility of the metals Cu, Fe, Mn, and Pd in GeTe in our experiments. Study of metal solubility and doping is a continuing topic of research for Kayla A. Cooley, who is also employing density functional theory calculations of metal-Ge-Te alloys. She plans to report her findings in her doctoral thesis to be completed in early 2020.

4. Project Participants and Training

Principal Investigator

- Prof. Suzanne Mohney

Post-doctoral Scholar

- Dr. Hamed Simchi

Doctoral Students

PhD Theses

- Kayla A. Cooley (with support some years from NSF Graduate Research Fellowship)
- Haila M. Aldosari (with scholarship from United Arab Emirates University)

Assisting with Processing or Characterization

- Alex Molina
- Shih-Ying Yu
- Katherine Kragh-Buetow

MS Student

MS Paper

- Kezhou Yang

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20. Cooley, Kayla A. and Mohney, Suzanne E., *J. Vac. Sci. Technol. A* **37** 061510 (2019)

Undergraduate Students

BS Thesis

- Zelong (Bruce) Ding

Assisting with Processing and Characterization

- Chavez Lawrence

5. Publications

1. "Impact of Premetallization Surface Preparation on Nickel-based Ohmic Contacts to Germanium Telluride: An X-ray Photoelectron Spectroscopic Study," Aldosari, Haila M.; Simchi, Hamed; Ding, Zelong; Cooley, Kayla A.; Yu, Shih-Ying; Mohney, Suzanne E., *ACS Applied Materials & Interfaces* 8 (50) 34802-34809 (2016) DOI: 10.1021/acsami.6b07412

2. "Factors Controlling the Resistance of Ohmic Contacts to Germanium Telluride," Aldosari, Haila M., Ph.D. Thesis, The Pennsylvania State University (2016). https://etda.libraries.psu.edu/catalog/kk91fk52b

3. "Thermal stability of low-resistance Au Ohmic contacts to GeTe," Aldosari, Haila M.; Cooley, Kayla A.; Yu, Shih-Ying; Kragh-Buetow, Katherine C.; Mohney, Suzanne E., *Thin Solid Films* 621, 145-150 (2017) DOI: 10.1016/j.tsf.2016.11.038

4. "Very Low-resistance Mo-based Contacts to GeTe," Aldosari, Haila M.; Cooley, Kayla A.; Yu, Shih-Ying; Simchi, Hamed; and Mohney, Suzanne E., *Journal of Applied Physics* **122(17)** 175302-1–175302-7 (2017) DOI: 10.1063/1.4990407

5. "Novel Sn-based Contact Structure for GeTe Phase Change Materials," Simchi, Hamed; Cooley, Kayla A.; Ding, Zelong; Molina, Alex; and Mohney, Suzanne E., *ACS Applied Materials & Interfaces* **10(19)** 16623–16627 (2018). DOI: 10.1021/acsami.8b

6. "Reactivity in Metal-Ge-Te Systems: Thermodynamic Predictions and Experimental Observations," Cooley, Kayla A. and Mohney, Suzanne E., *Journal of Vacuum Science and Technology A* **37** 061510-1–061510-24 (2019). DOI: 10.1116/1.5126109

7. "Review of Electrical Contacts to Phase Change Materials and an Unexpected Trend between Work Function and Contact Resistance to Germanium Telluride," Kayla A. Cooley, Haila M. Aldosari, and Suzanne E. Mohney, in preparation.

6. Awards

1. Best Poster from the Electronic Materials and Photonics Division of AVS, 2017. (Kayla A. Cooley, Haila M. Aldosari, Hamed Simchi, Johnathan O'Neill, Shih-Ying Yu, Alex Molina, and Suzanne E. Mohney, "An Unexpected Trend Between Metal Work Function and Contact Resistance to Germanium Telluride," [Late News] AVS International Symposium, Tampa, FL, October 2017.)

7. Interactions/Transitions

7.1 Interaction with Industry

This project was conducted in large part using sputtered amorphous or polycrystalline GeTe films generously supplied by Northrop Grumman Electronic Systems. We also discussed our data on surface preparation, contact resistance, and materials characterization on conference calls with Dr. Robert Young and his colleagues.

7.2 Interaction with Government Laboratories

We interacted with Drs. Laura Ruppalt and James Champlain at the Naval Research Laboratory, including testing of some samples prepared at the Naval Research Laboratory, and had fruitful discussions with these researchers.

7.3 Conference Presentations and Seminars

1. "Impact of Pre-Metallization Surface Preparation and Metallurgical Reactions on Ohmic Contacts to Germanium Telluride," Haila M. AlDosari, Hamed Simchi, Zelong Ding, and Suzanne Mohney, MRS Spring Meeting, Phoenix, AZ, March 2016.

2. "Pre-Metallization Surface Treatment of Germanium Telluride," Hamed Simchi, Haila M. Aldosari and Suzanne E. Mohney, 58th Electronic Materials Conference, Newark, DE, June 2016.

3. "Thermal Stability of Low-Resistance Ohmic Contacts to Germanium Telluride," Haila M. Aldosari, Hamed Simchi, Kayla Cooley, Zelong Ding, Shih-Ying Yu and Suzanne E. Mohney, 58th Electronic Materials Conference, Newark, DE, June 2016.

4. ***Best Poster Award Winner***: Kayla A. Cooley, Haila M. Aldosari, Hamed Simchi, Johnathan O'Neill, Shih-Ying Yu, Alex Molina, and Suzanne E. Mohney, "An Unexpected Trend Between Metal Work Function and Contact Resistance to Germanium Telluride," (Late News) AVS International Symposium, Tampa, FL, October 2017.

5. "Ultra-Low Resistance Sn-Based Contacts to GeTe," Hamed Simchi, Kayla Cooley, and Suzanne Mohney, Spring MRS Meeting, Phoenix, AZ, March 2017.

6. "Record-Low Contact Resistances to Many Semiconductors" (poster partly from this project) K. A. Cooley, T. N. Walter, A. C. Domask, A. Molina, A. Agyapong, C. Lawrence, L. Kerstetter, and S. E. Mohney, Materials Day, University Park, PA, October 2017.

7. ***Invited:*** "Design of Contacts for Semiconductor Devices," (partly from this project) Suzanne E. Mohney, Nelson W. Taylor Lecture Series in Materials Science and Engineering, University Park, PA, April 2018.

8. ***Invited:*** "Metal Contacts to Semiconducting Chalcogenides: Examples from 2D and 3D Materials," (partly from this project) Suzanne E. Mohney, Kayla A. Cooley, Anna C. Domask, Michael Abraha, Haila AlDosari, Rajeh Alsaadi, Hamed Simchi, and Timothy N. Walter, AVS Meeting, Long Beach, CA, October 2018.