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Characterization of room temperature metal microbolometers near the metal-insulator transition regime for scanning thermal microscopy

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Metal microbolometers, used in scanning thermal microscopy, were microfabricated from <20 nm titanium thin films on $SiO_2/Si_3N_4/SiO_2$ cantilevers. These thin films are near the metal-insulator transition regime such that as the film thickness decreases—the resistance increases and the current-voltage characteristics cross over from sublinear to superlinear. In addition, the temperature coefficient of resistance transitions from positive to negative before it plateaus at a negative value. Thin titanium films exhibit negative temperature coefficient of resistance as high as $-0.0067/\text{K}$ which is higher than that of bulk titanium films. © *2009 American Institute of Physics*. [doi:10.1063/1.3250434]

Uncooled microbolometers are currently used in the manufacture of highly specialized thermal imaging applications such as night vision and scanning thermal microscopy (SThM).[1–3] In order to operate effectively, microbolometers must have a high temperature coefficient of resistance (TCR) and low noise characteristics. In addition, the materials used to manufacture microbolometers must be inexpensive and compatible with current complementary metal-oxide-semiconductor (CMOS) processes. These are the primary conditions that have to be met as part of the continuing effort to develop even smaller, better performing microbolometers that weigh less and consume less power.

To date, various materials have been used to fabricate microbolometers. Polycrystalline and amorphous silicon have a high temperature coefficient of resistance (up to $0.05/\text{K}$) but exhibit adverse noise characteristics.[4–6] Vanadium oxide, on the other hand, has a TCR of approximately $0.05/\text{K}$ and a superior noise equivalent temperature difference (NETD). However, vanadium oxide introduces a significant number of deposition problems.[6–8] Thin film metallic microbolometers, in contrast, have very low noise characteristics in addition to a low TCR ($0.005/\text{K}$).[6,9]

Two types of SThM microbolometers have shown considerable promise: Doped silicon microbolometers, with TCRs between 0.003 and $0.0056/\text{K}$ that are integrated into single-crystal silicon cantilevers,[10,11] and metallic microbolometers with a TCR of around $0.0029/\text{K}$.[12] Thin film metallic microbolometers have other important advantages as well, including simplified fabrication and a lower manufacturing cost. Metallic microbolometers also enable the use of alternative substrate materials (such as polymers), that tend to exhibit higher compliance properties and improved thermal isolation for better temperature resolution.

The electrical properties of granular metals vary as the composition of a metal and nonmetal mixture changes.[13] Metal deposition goes through four phases before it starts behaving like a bulk film: nucleation, island formation, formation of island networks, and formation of continuous (but porous) film.[14–17] The first three phases are considered discontinuous. Typically, island films have negative TCRs while porous films have a positive TCR.[14,15,18–20] However, the TCR for porous films is lower than that of a thick, bulk film. It is well established that there exists a metal-insulator or a superconductor-insulator transition as a function of film thickness for metal films at cryogenic temperatures. It is interesting to note that this transition typically occurs for films with a resistance on the order of quantum resistance. We have evaluated titanium films that are close to the metal-insulator transition (MIT) regime. However, instead of evaluating their cryogenic transport properties, we have focused on their operation as thin film microbolometers (at room temperature) and quantified the relationship between TCR, resistance, and film thickness.

In the process, we developed an ultrathin film (<20 nm) titanium microbolometer which is integrated onto a $SiO_2/Si_3N_4/SiO_2$ (ONO) cantilever with a Si/SiO_2 tip intended for scanning thermal microscopy. Wafers with different thicknesses of titanium were also prepared and tested. The morphology of these metal thin films (discontinuous form versus continuous form)[18] is revealed by measuring their electrical properties. Details regarding the fabrication of the devices, the results of *I-V* and TCR measurements, and a scan using these microbolometers are presented.

Four microbolometer probe designs were fabricated [Fig. 1(a)]. The first two designs were rectangular with 100×100 and 100×220 μm^2 areas and the second two designs were triangular with 100 and 220 μm wide bases and 64 and 160 μm long, respectively. The cantilevers were made from a 1.1 μm thick ONO layer with 10 μm long Si/SiO_2 tips. A metal film was deposited covering the tip area to form the

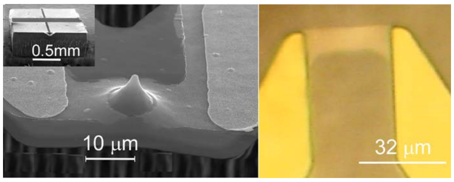

FIG. 1. (Color online) (a) Scanning electron microscope (SEM) of microbolometer probe. Inset: SEM of the chip. (b) Picture of titanium resistors on a wafer.

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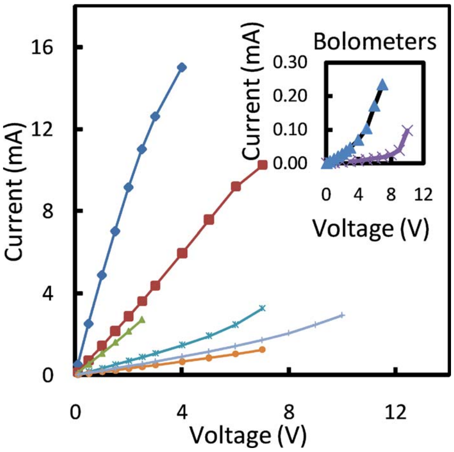

FIG. 2. (Color online) *I-V* characteristics of resistors on SiO2/Si wafers with two terminal Ohmic resistances between 200 Ω and 6.37 kΩ and of bolometer probes with two terminal Ohmic resistances between 72.5 and 550 kΩ in the inset.

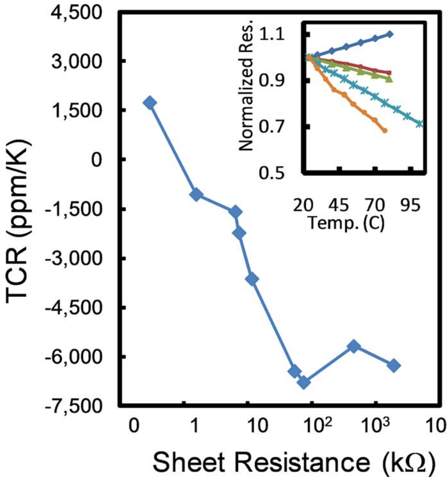

FIG. 3. (Color online) Plot of the TCR as a function of sheet resistance for different devices. Inset normalized sheet resistance vs temperature.

microbolometer, while a gold layer was deposited on the top of the metal film, excluding the tip area for electrical contact. $3\times1.4\times0.5$ mm^3 chips held the cantilevers. The fabrication process included tip formation by isotropic deep reactive-ion etching (DRIE) dry etching with an oxide layer as etch mask; tip sharpening by growing 1 μm thermal oxide followed by a BHF oxide removal step, 1.1 μm thick low-pressure chemical vapor deposition (LPCVD) ONO layer deposition on the Si substrate, cantilever patterning by a sequence of ONO etching steps, tip area SiO_2/Si_3N_4 layer removal, metals patterning with a series of lift-off processes, wafer back side etching for device release, and 20 nm of aluminum back side deposition.

In addition, three different wafers were prepared with titanium resistors having thicknesses between 10 and 20 nm, deposited on SiO_2. As shown in Fig. 1(b), a 10 μm wide titanium film was deposited on the substrate to form a resistor. The lengths of the titanium resistors vary from 14 to 32 μm. 150 nm thick gold film was deposited on top of the titanium traces excluding the tip area creating leads and leaving exposed a narrow rectangular titanium thin film at the tip area. The Ti films were expected to form a native oxide soon after the films were exposed to the ambient environment. However, the bolometers were found not to be vulnerable to film degradation as a result of additional oxidation. The resistors have also been analyzed over a 2 month period and the drift in base line resistance has been consistently less than 2%.

I-V measurements were also performed on a probe station. The *I-V* characteristics of resistors on SiO_2/Si wafers with two terminal Ohmic resistances between 200 Ω to 6.37 kΩ and bolometer probes with two terminal Ohmic resistances between 72.5 and 550 kΩ are illustrated in Fig. 2 and the inset, respectively. The *I-V* curves exhibit a sublinear behavior at two-terminal Ohmic resistance values below 1 kΩ. As the two-terminal Ohmic resistance increases above 1 kΩ, the *I-V* curves exhibit superlinear characteristics. At values close to 1 kΩ/□, the *I-V* curves begin to approximate a linear behavior.

The TCR was then measured using a calibrated microheater plate with an atomic force microscope (AFM). The bolometer probe tips were brought in contact with the microheater plate. Temperatures were varied from 20 ± 0.1 to 101 ± 0.1 °C. Sheet resistance values were calculated using the two-terminal Ohmic resistance from the equation $R\square = WR_{2t}/L$, where $R\square$ is the sheet resistance, R_{2t} is the two-terminal Ohmic resistance, W is the width, and L is the length of the device. A number of bolometer probes with sheet resistances between 7.3 and 1920 kΩ/□ were tested and the results are shown in Fig. 3. TCR measurements of the resistors on a substrate were also performed using a microheater plate under a probe station. A number of resistors on a wafer with sheet resistances between 0.29 and 6.4 kΩ/□ are shown in Fig. 3.

In the inset of Fig. 3, five plots of normalized sheet resistance, $R\square(T)/R\square(300K)$ versus temperature are shown. The normalized sheet resistances in Fig. 3 correspond to resistors on a wafer with sheet resistances of 0.29, 1.57, and 6.4 kΩ/□, and microbolometers with sheet resistances of 11.6 and 74.9 kΩ/□. From the inset of Fig. 3, it can be observed that as the resistance increases, the slope of the sheet resistance versus temperature changes from positive to negative. The TCR values obtained from such measurements are plotted as a function of sheet resistance in Fig. 3. With increasing sheet resistance, the TCR values first shift from positive to negative and then continue to decrease until they plateau (after a specific resistance value). There is an optimal sheet resistance beyond which there is no improvement in bolometric sensitivity. For the titanium films studied, this value was measured at approximately 74.9 kΩ/□ with a minimum TCR value of around −6790 ppm/K.

We also performed noise measurements on three bolometers with resistance values ranging from 14 to 410 kΩ/□. The bolometers were found to exhibit $1/f$ noise. By measuring the power noise spectral density, we extracted the noise parameter K using $S_I(f)=KI^2/\upsilon f$, where $S_I(f)$ is the noise spectral density function, I is the bias current, υ is the bolometer volume, and f is frequency. K values for the three bolometers ranged from 10^{-22} to 5×10^{-21} cm^3. Like the vanadium oxide films, K increases with increasing film resistance. However, the level of noise was lower than that of vanadium oxide films.[21]

Another sheet resistance value of interest is near 1 kΩ/□ where the TCR is close to zero. This is useful for applications that require resistors that are not influenced by

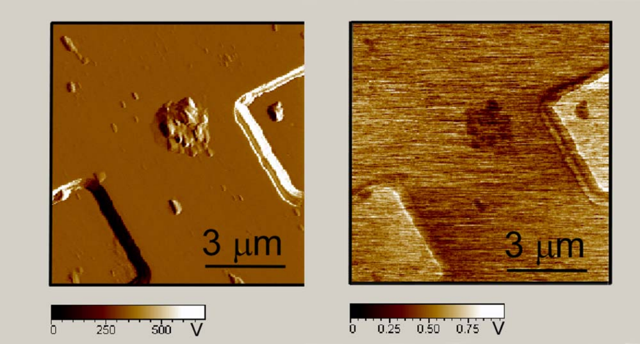

FIG. 4. (Color online) (a) Topographical and (b) thermal scan.

temperature fluctuations. These two results may be combined in order to develop microbolometers where the sensing area would be of a thickness that would provide the highest TCR in absolute values, while the electrodes would be of a thickness with near zero TCR.

Similar to the crossover from sublinear to superlinear I-V characteristics, the transition from positive to negative TCR also occurs at around $1\ \mathrm{k}\Omega/\square$. The nonlinearity of the I-V characteristics can be understood within the context of Joule heating. The electron temperature of the film can be estimated by calculating the thermal resistance through the substrate. The electron temperature with the TCR measurements explains the nonlinearity of the I-V characteristics.

The titanium thin film bolometers can be utilized in scanning thermal microscopy. Using an AFM, a thermal signal from the thermal probes is fed into an interface circuit.[22] The interface circuit is then connected to the controller of a PicoMAPS AFM from Agilent. Figure 4 illustrates topographical and thermal images obtained simultaneously when a patterned sample is scanned by the bolometer probe. The sample is a silicon calibration grating with 10 μm long and 200 nm deep pitches. The probe resistance change is related to the output voltage change which is proportional to the supplied power change. The supplied power change is equal to the conductive heat loss between the tip and sample which is proportional to the change in the thermal conductance of the sample. Therefore, the plot of the circuit output voltage represents the thermal conductance changes of the sample.

These scans were performed with a $7.2\ \mathrm{k}\Omega/\square$ thin film titanium probe with a measured TCR of -3638 ppm/K. Submicron features are visible. The NETD, which is also dependent on the circuitry, is calculated from Ref. 23 to be approximately 18 mK. These microbolometers have operating temperatures of up to 115 ± 0.1 °C. Significant improvements in the NETD can be made by using more advanced circuitry.[24] The probe design can be improved by further confining the bolometer thin film to the tip area. The TCR can be further improved by using alternative materials at the MIT regime that may provide a higher TCR.

In conclusion, titanium thin film properties have been studied near the MIT regime in order to improve the sensitivity of titanium microbolometers. Sheet resistances corresponding to the highest TCR and the lowest TCR, in absolute values, were determined. The relationship between TCR and resistance may be typical for many metal and semimetal thin films near room temperatures. These findings were then used to develop scanning thermal probes. Applications of metal or semimetal films with resistances thicknesses near the MIT can be extended to infrared imaging and chemical sensing. Further study of metals and semimetal films is subsequently needed in order to determine the highest TCR as well as the lowest noise characteristics.

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