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Cryogenic (4K) Measurements of Some Resistors and Capacitors

A. R. Kerr and M. Lambeth
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Abstract: **This note describes measurements of some chip capacitors and thin-film resistors at 4.2 K. The capacitors have the following dielectrics: SiO_2, ATC types CA and CC, and ATC type 700A. The resistors are TaN and nichrome thin film made by Mini-Systems, Inc.**

Resistors and capacitors specified for operation in the standard military temperature range (−55°C to +125°C) may have substantially different characteristics at cryogenic temperatures (~ −270°C). For many years it has been known that resistors and attenuators using nichrome thin films could be used in cryogenic systems. However, TaN has largely replaced nichrome for use in commercial resistive thin-film microwave components. About 1980, we found that TaN resistors from one manufacturer changed substantially at ~ 4 K – this did not seem surprising given that Ta and TaN are listed as superconductors with critical temperatures in the range 4.4 – 14 K [1]. In recent years, NRAO has successfully used TaN resistors in many cryogenic applications at temperatures between 4 K and 15 K. Apparently, the suitability of TaN components for cryogenic operation depends on the particular process used to fabricate the films.

The Mini-Systems MSMT series of RC networks [2] uses TaN thin-film resistors and parallel-plate capacitors with a SiO_2 dielectric. They rely on the conductivity of the silicon substrate to connect the lower plates of capacitors to the ground metalization on the backside of the substrate. We were concerned that carrier freeze-out at ~ 4 K might effectively disconnect the capacitors from ground.

The Mini-Systems WATF series of chip resistors [3] are available with TaN or nichrome thin films and different substrate materials. The one tested here has a nichrome film on an alumina substrate.

Past experience at NRAO has indicated that porcelain and ceramic multi-layer chip capacitors [4], and ATC 111 single-layer capacitors [5] with dielectric types A (K = 14), BB (K = 31), or CA (K = 60), do not change substantially between room temperature and ~ 12 K, and amplifiers employing these capacitors have operated well at 4.2 K. It was not known whether capacitors with dielectric type CC (K = 130) would be useable at ~ 4 K.

The measurements described here were made on the following components:

Capacitors:
- ATC 700A160JCA150X – 16 pF porcelain and ceramic multi-layer chip capacitor.
- ATC 111UCA3R9C100TT – 3.9 pF single-layer capacitor with type CA dielectric.
- ATC 111UCC3R9C100TT – 3.9 pF single-layer capacitor with type CC dielectric.
- Mini-Systems MSMT 210-0418 – 16 pF parallel-plate capacitor with SiO_2 dielectric.
- NRAO lead transition – a quartz standoff chip allowing connection of a heavy wire, attached by solder, to a thin bond wire.

Resistors:

- Mini-Systems MSMT 210-0418 – 5 ohm TaN resistor.
- Mini-Systems MSMT 210-0418 – 50 hm TaN resistor.
- Mini-Systems MSMT 210-0418 – 1000 ohm TaN resistor.
- Mini-Systems WATF 7AN50R00J-HWU – 50 ohm nichrome resistor.

Capacitor Measurements

The capacitor to be measured was mounted on a metal ground plane with Epotek H20E conductive epoxy and connected to the center conductor of an SMA connector via a short gold bond-wire. This fixture was connected through a 4-foot length of stainless steel 50-ohm coaxial cable to a 1 kHz digital capacitance meter [6]. With the capacitor disconnected, the capacitance of the cable and fixture was measured at room temperature and with the fixture immersed in liquid helium (4.2 K). The measurements were repeated with the capacitor connected, and its capacitance determined as the difference between the reading and the open-circuit capacitance.

In AC bridge measurements using a long cable between the bridge and the unknown, the electrical length of the cable can introduce an apparent capacitance offset in addition to the static capacitance of the cable. In the present measurements it was shown by measuring the same capacitor at room temperature with and without the cable that the length of cable had no significant effect on the results. The absolute accuracy of the capacitance meter, as given by its manufacturer for the range used, is ± (1 % of reading + 0.2 pF), which is ± 0.36 pF or 2 % for a 16 pF capacitor. The repeatability is ± 0.1 pF.

Capacitor Nominal value / Dielectric	Room temp pF	4 K pF	Increase on cooling
ATC 700A160JCA150X 16 pF ± 5 % / porcelain & ceramic	16.9	17.1	+0.2 ± 0.2 pF
4 x ATC 111UCA3R9C100TT 4 x (3.9 pF ± 0.25 pF) / CA	16.0	15.1	−0.9 ± 0.2 pF
4 x ATC 111UCC3R9C100TT 4 x (3.9 pF ± 0.25 pF) / CC	15.8	19.1	+3.3 ± 0.2 pF
Mini-Systems MSMT 210-0418 16 pf ± 5 % / SiO_2	16.6	16.7	+0.1 ± 0.2 pF
NRAO lead transition – / SiO_2	1.2	1.4	+0.2 ± 0.2 pF

Resistor Measurements

The 5-ohm and 50-ohm resistors were measured using a 4-wire ohm-meter [7]. The 1000-ohm resistor was measured with a two-wire configuration, corrected for lead resistance, using the same instrument. The results are shown in the table. The accuracy of the 4-wire ohm-meter given by its manufacturer for the range used is ± (0.01 % of reading + 0.01 ohm), which corresponds to ± 0.015 ohm for a 50-ohm resistor and ± 0.01 ohm for a 5-ohm resistor. Mini-Systems' tolerance on the resistor values is 1 %.

Mini-Systems TaN and Nichrome Resistors

Resistor	Type	Room temp. ohms	4 K ohms	% increase on cooling
5 ohm 1 %	TaN	4.95	4.98	0.6 %
50 ohm 1 %	TaN	50.08	51.54	2.9 %
50 ohm 5 %	Nichrome	49.52	49.69	0.3 %
1000 ohm 1 %	TaN	999	1029	3.0 %

Discussion & Conclusions

Capacitors: The ATC 700 porcelain and ceramic capacitor, and the two quartz capacitors exhibited no change on cooling to 4 K, within the measurement error. The ATC 111 CA capacitor decreased in value by 6 %, and the ATC 111 CC capacitor increased by 21 %.

Concern that, for the Mini-Systems MSMT RC network, carrier freeze-out might isolate the capacitors from ground turned out to be unfounded. These capacitors exhibited no measurable change between room temperature and 4 K. The absence of carrier freeze-out in the silicon substrate is explained by the fact that in heavily doped Si the impurity ionization energy vanishes and the carrier density is independent of temperature [8]. The MSMT chips use boron doped 111-oriented silicon with resistivity 0.001-0.005 ohm-cm, which corresponds to a doping density > 10^{19} cm^{-3}.

Resistors: Consistent with past experience with nichrome thin-film resistors, the resistance of the 50-ohm nichrome resistor increased only 0.3 % on cooling to 4.2 K. The TaN resistors increased on cooling from room temperature to 4.2 K as indicated in the table – less than 1 % for the 5-ohm resistor, and ~ 3 % for the 50- and 1000-ohm resistors. This indicates that these TaN resistors do not undergo a superconducting transition at or above 4.2 K. Given our past experience, and the fact

that TaN is listed as a superconducting compound [1], it would seem wise to test TaN resistors destined for cryogenic operation to verify that there is no unacceptable change on cooling.

Acknowledgment

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References

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[3] http://www.mini-systemsinc.com/msithin/Thin_%20Film_%20Catalog.pdf

[4] http://www.atceramics.com/products/multilayer_capacitors.asp

[5] http://www.atceramics.com/products/dielectric_specifications.asp

[6] GW Instruments digital LCR meter model LCR-814.

[7] HP digital multimeter model 34401A.

[8] P. W. Chapman, O. N. Tufte, J. D. Zooke, and D. Long, "Electrical Properties of Heavily Doped Silicon," J. Appl. Phys., vol. 34, no. 11, pp. 3291-3295, Nov. 1963.