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RF Burnout Power of SIS Mixers

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Abstract – The RF burnout power of Nb/Al-AlOx/Nb SIS mixers is estimated from measured DC burnout data. It is assumed that an SIS junction suffers permanent damage when it reaches a critical temperature which is the same for all junctions of that material type. The junction temperature depends on the power (RF or DC) dissipated in the junction and the thermal resistance between the junction and thermal ground. The burnout powers of some SIS receivers currently in use at millimeter-wave observatories are estimated.

1. Introduction

With the launch of CloudSat in April 2006, the possibility that sensitive millimeter-wave receivers on radio telescopes might be damaged by excessive RF power ceased to be a purely academic concern. CloudSat has a 94-GHz down-looking 1.8 kW radar transmitting 3-μs pulses at a 4300 Hz repetition rate. The peak power falling on a 12-m aperture on the ground directly below the transmitter is 60 mW. This note estimates the RF burnout power levels of SIS mixers as a function of junction size and number of junctions, from which the burnout power of the 3-mm SIS receivers currently in use at radio observatories is deduced.

2. Thermal Resistance of an SIS junction

Most SIS junctions consist of an insulating tunnel barrier sandwiched between two superconducting electrodes on an insulating substrate. When heat is generated by DC or RF power dissipation in the junction, the temperature rise in the junction is proportional to the thermal resistance between the junction and thermal ground. There are two parallel paths by which heat can flow from the junction: through the electrodes, and through the substrate. In practice, one path will probably have much higher thermal resistance than the other and can be ignored. However, we do not know the relative magnitudes of the two thermal resistances, so both will be considered.

An earlier discussion [1] of the dependence of burnout power on junction size in SIS mixers assumed that the burnout power was simply proportional to the junction area. This would be the case for a junction formed between the ends of two cylindrical conductors equal in diameter to the junction; the thermal resistance between junction and thermal ground is then inversely proportional to the junction area. However, that does not correspond the structure of the tunnel junctions in SIS mixers as described above.

Thermal Resistance of the Electrodes: To determine the thermal resistance of an SIS junction, we borrow from the analysis of the electrical resistance of a Schottky diode by Carlson *et al.* [2]. In the regions of the electrodes immediately below and above the junction, heat flow lines are approximately hyperbolic (ellipsoidal isotherms) as the heat enters the metal and spreads out to flow radially in the region beyond the junction. In this region, the spreading resistance

$$R_{sp} = \frac{\rho}{2\pi a}\arctan\frac{t}{a} \ , \qquad (1)$$

where a is the radius of the tunnel junction, t is the thickness of the electrode metal, and ρ is its thermal resistivity. The spreading region extends to radius $\sqrt{a^2+t^2}$, beyond which radial sheet flow is assumed to a large radius b. The sheet resistance of that region

$$R_{sh} = \frac{\rho}{2\pi t} \ln \frac{b}{\sqrt{a^2 + t^2}} \,. \qquad (2)$$

Thermal Resistance of the Substrate: Heat from the tunnel junction entering the thick substrate spreads out with hyperbolic flow lines (ellipsoidal isotherms). The thermal resistance of the substrate out to radius r is

$$R_{sub} = \frac{\rho}{2\pi a} \arctan \frac{r}{a} \,.$$

For a thick substrate, $r \gg a$ so

$$R_{sub} = \frac{\rho}{2\pi a} \,. \qquad (3)$$

3. Thermal Resistance Ratio for Junctions of Different Sizes

Using equations (1)-(3), the ratio of thermal resistances of two SIS junctions of different size can be estimated when heat conduction is either through the electrodes or through the substrate. In Fig. 1, this ratio is shown for the two conduction paths, with the thermal resistance normalized to that of a reference junction, a 1.8-µm diameter (2.54 µm^2) junction measured in a burnout test at NRAO. The light blue lines in the figure indicate the junction sizes currently used in 3-mm SIS receivers at several radio observatories.

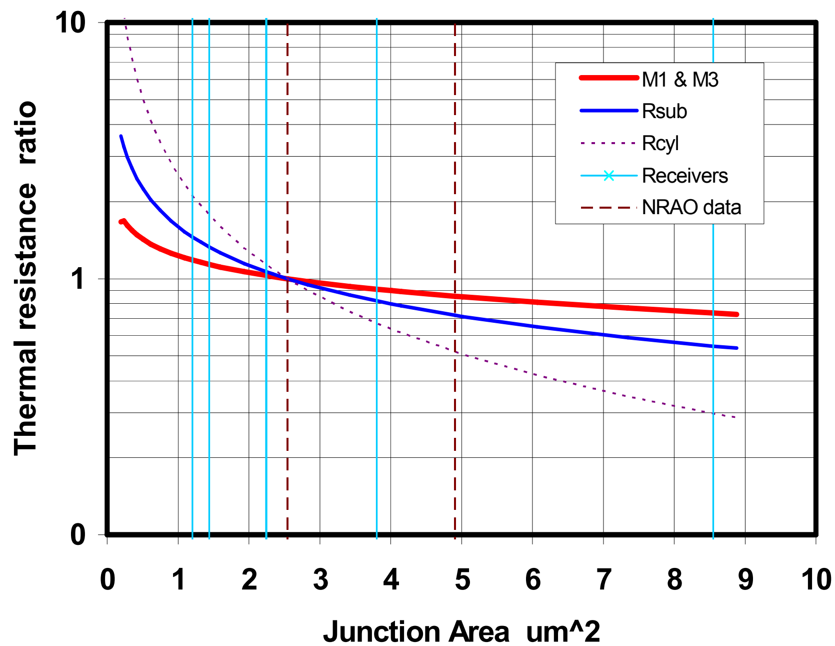

Fig. 1. Thermal resistance ratio of SIS junctions when conduction is (red curve) through the metal electrodes, (blue curve) through the substrate, assumed thick, and (dotted curve) through cylindrical contacts of the same cross-sectional area as the junction. All curves are normalized to the thermal resistance of a 1.8-µm diameter (2.54 µm^2) reference junction. The light blue lines indicate the junction sizes currently in use in 3-mm receivers at OSO, BIMA, BIMA, ALMA, ARO 12-m, IRAM (Plateau de Bure), IRAM (Pico Valeta).

From Fig. 1, it would be expected, for example, that a 4.91-µm^2 junction would have 85% of the thermal resistance of the 2.54-µm^2 reference junction when heat conduction is through the electrodes, and 72% when conduction is through the substrate.

It is seen that the thermal resistance curves for the electrodes and the substrate are within 23% over the range of junction sizes in use in 3-mm receivers – not a serious difference in the context of burnout power estimation. This means that a knowledge of the absolute thermal resistances of the two paths is not essential to an approximate determination of burnout powers,

4. Burnout Tests on SIS mixers

There appears to be little data on the burnout characteristics of the SIS junctions used in radio astronomy. The only relevant data we have are from DC burnout tests done at NRAO [1], as shown in Table I. In that experiment, the SIS chip at 4 K in a vacuum cryostat was biased with DC in increasing steps until a permanent change was seen in the I(V) characteristic after one minute at the same current. This was done with two SIS mixers as indicated in the table. The failure in both cases was due to one or more junctions becoming a near short-circuit.

TABLE I
NRAO SIS junction burnout tests – March 1996

	SIS Chip 1	**SIS Chip 2**
Junction type	Nb/Al-AlOx/Nb trilayer	Nb/Al-AlOx/Nb trilayer
Junction diameter	1.8 µm	2.5 µm
Junction area	2.54 µm^2	4.91 µm^2
No. of junctions in series	6	6
Substrate	Fused quartz	Fused quartz
Damage power	34 mW	37 mW

To extrapolate this very limited data to RF power limits for mixers with different junction sizes and with different numbers of junctions in series requires several major assumptions:

1) Damage to an SIS junction is determined by the temperature to which it is heated by the DC current.

2) The RF and DC power required to damage a junction are the same.

3) The thermal connection to an SIS junction is either:
(a) primarily through the upper and lower electrodes, in which case the electrodes of the junctions under discussion are assumed to have the same thickness, or
(b) primarily through the substrate.

4) In a series array of SIS junctions, the temperature of each junction is not affected by dissipation in the neighboring junctions, so the damage power level of an array of N junctions is simply N times that of a single junction of the same size as those in the array.

Of these, assumptions 3(a) and 4 are the most questionable.

5. Burnout Power Estimates

To estimate the burnout power of an actual SIS receiver, the thermal resistance ratio for the relevant junction size (relative to the 2.54-μm^2 reference junction) is determined from Fig. 1. The burnout power for the single junction is equal to the burnout power for the reference junction* divided by the thermal resistance ratio. For the whole receiver, the burnout power is the single junction quantity multiplied by the total number of junctions in the receiver to which the antenna power is coupled. Fig. 2 shows the calculated burnout power (per junction) as a function of junction area when thermal conduction is via the electrodes or via the substrate. The NRAO burnout test data are shown as individual points.

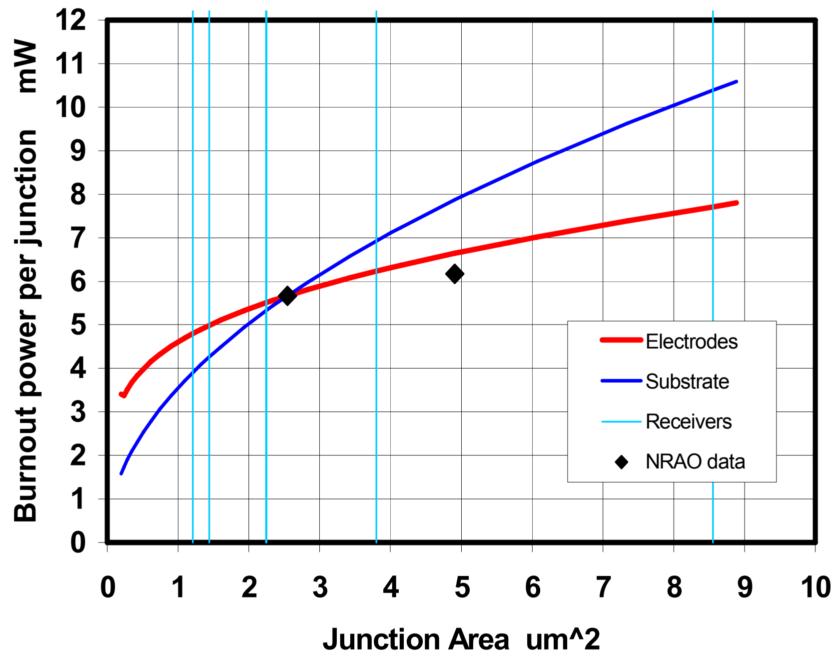

Fig. 2. Estimated burnout power of an SIS junction, as a function of area, when conduction is (red curve) through the metal electrodes and (blue curve) through the substrate, assumed thick. The results are deduced from the measured burnout power of a 2.54-μm^2 junction. The NRAO burnout test data are shown as discrete points. The light blue lines indicate the junction sizes currently in use in 3-mm receivers at OSO, BIMA, BIMA, ALMA, ARO 12-m, IRAM (Plateau de Bure), IRAM (Pico Valeta).

In Table II, these estimates of burnout power are applied to the 3-mm receivers currently in use at several radio astronomy observatories. It is assumed that thermal conduction is primarily through the substrate (blue curves in Figs. 1 & 2) as opposed to the electrodes (red curves). Within the range of junction sizes used in 3-mm SIS receivers, the two curves differ by no more than 25%, but the substrate thermal resistance ratio is higher for small junctions, which are more susceptible to burnout, so it is the more conservative choice.

Using the same method, the burnout power of an array of six 4.91-μm^2 junctions should be 47 mW. This compares with the measured 37 mW (Table I).

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* Note that the reference junction is one junction of the six-junction array measured in the NRAO burnout test – see Table I.

TABLE II
Estimated damage power levels for 3-mm receivers at several observatories.
It is assumed that all mixers use Nb/Al-AlOx/Nb SIS junctions on fused quartz substrates.

Observatory	Mixer type	Junction area μm^2	Total no. of junctions	Thermal resistance ratio	Damage Power mW
ALMA	2SB	3.80	8	0.82	55
CARMA 6-m	DSB	1.21	1	1.45	4
CARMA 6-m	DSB	2.24	1	1.07	5
CARMA 10-m	DSB	1.44	2	1.33	9
CARMA 10-m	DSB	3.8	4	0.82	27
IRAM – Plateau de Bure	1SB	4.00	2	0.80	14
IRAM – Pico Valeta	2SB	2.25	6	1.07	32
IRAM – Pico Valeta	2SB	1.44	4	1.33	17
Kitt Peak 12-m	DSB	8.55	6	0.55	62
Onsala	2SB	4.01	2	0.80	14

6. Discussion

It is emphasized that the SIS mixer burnout powers shown in Fig. 2 and Table II are approximate. They are subject to the assumptions given in section 4 above and are for mixers with Nb/Al-AlOx/Nb SIS junctions on fused quartz substrates, which is the case for most 3-mm SIS mixers currently in operation.

When the RF signal is pulsed, as from a radar transmitter, the relative sizes of the pulse width and the thermal time constant of the SIS mixer must be considered. If the thermal time constant is shorter than the pulse width, the junction will reach the same temperature for a given peak pulse power as for a CW signal of the same power. If the thermal time constant is greater than the pulse width, the junction temperature will never reach the CW value, and a greater peak pulse power will be tolerable. It is assumed here that the mixer time constant is shorter than the radar pulse width. This is supported by the observation that, in HEB mixers made of the same materials, the IF bandwidth is generally a few GHz, corresponding to a thermal time constant ~0.1 ns, much shorter than the 3-µs CloudSat radar pulses. (Although the geometry of HEBs and SIS mixers is different, the difference would be expected to reduce further the ratio of the time constants of the SIS mixer and the HEB.)

As the thermal conduction path (through the metal electrodes or through the substrate) is not known, it has been assumed to be through the substrate. This should not introduce a large error if it turns out that conduction is primarily through the electrodes. If the thermal conduction path is through the electrodes, then it is likely that the temperature of each junction will not be independent of the heating of the neighboring junctions as has been assumed, which would result in an overestimate of the burnout power of the array. A more accurate thermal analysis of an SIS mixer is complicated by the wide range of temperatures involved – 4 K to several hundred K at which the SIS junction is permanently damaged – over which the thermal properties of the substrate and superconducting electrodes will change substantially.

Acknowledgments

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References

[1] A. R. Kerr, email to W. Brundage, NRAO, 20 March 1996.

[2] E. R. Carlson, M. V. Schneider, T. F. McMaster, "Subharmonically Pumped Millimeter-Wave Mixers," IEEE Trans. Microwave Theory Tech., vol. 26, no. 10, pp. 706-715, Oct. 1978.