Transition Edge Operation of Tantalum Diffusion-Cooled Hot-Electron Bolometers

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Diffusion-cooled hot-electron bolometers (HEB's) differ from the phonon-cooled variety in that the electron temperature distribution inside the device has an approximately parabolic shape, instead of being essentially uniform. As a result, the electron temperature Te is close to the transition temperature Tc only in a small portion of the device, and it is only that portion that can generate thermal fluctuation (TF) noise and that can contribute to the frequency conversion in a mixer. Heat from the DC current is dissipated in any parts of the device that are in the normal state, while RF heat dissipation (above the gap frequency) is uniform throughout the device. The internal temperature distribution is determined by this heat dissipation and the dominant heat transport mechanism, which is electron diffusion, as described by the Wiedemann-Franz law. The difference in heat conductivity between the superconducting and the normal-conducting regions of the device should also affect the heat transport, as should Andreev reflections at the interface between the regions. For a thorough description of these effects and others, the reader is referred to [1].

In a simple model the electron temperature inside the device is close to Tc only in some limited regions of the device, as marked in Fig. 1. For the bias conditions B and C in Figs. 1 and 2, which can be reached at least theoretically, these regions are quite small. For bias point A the normal conducting part of the device is quite small, and as a result the bias current needs to be higher in than at point B in order to dissipate a sufficient amount of heat to support the temperature distribution. This creates the region of negative differential resistance around point A that cannot be easily reached experimentally due to instability.

With a sharply defined transition, the model in Fig.1 reduces to the hot-spot model [2], where mixing is achieved by the expansion and contraction of the central normal region as a response to modulation of the heat dissipation by the signal and local oscillator (LO) voltages. In laboratory measurements a finite transition width is always seen in small devices. The reason may be variations in the actual Tc between different grains in the device film, or possibly that the transition is widened by the thermodynamic energy fluctuations themselves. A small piece of the device (about the size of a few coherence lengths) will have a fluctuating energy content, so that if the electron temperature is close to Tc it could at some times be in the normal state and at other times superconducting. This could at least partially explain the measured transition width, and could also justify the use of a finite transition width in simplified mixer calculations to represent that mixing can occur also in regions that are slightly above or below the nominal Tc. It would seem that only a small amount of thermal fluctuation noise could be generated and only low conversion efficiency could be achieved at bias points B and C in Figs 1 and 2, since such small parts of the device are close to the Tc. However, this is not necessarily the case when the bias is close to point B, where the dc bias circuit device combination becomes unstable. Close to that point even small variations in heat content can result in significant voltage shifts, which constitute output noise when those variations are due to thermal fluctuations, and intermediate frequency output power when they are due to the beating between the signal and the LO in a mixer. Since this is in principle caused by a feedback effect, the bandwidth of these parameters will be affected.

Experimentally, the Tc does not seem to be uniform throughout a device, and in short bolometers a "foot" structure appears in the resistance-versus-temperature (R vs. T) curve. This structure, which is present in both tantalum and niobium devices and is even more pronounced in those made from aluminum, appears to be associated with the ends of the microbridge. One explanation for this effect is that the superconducting gap is suppressed at the ends due to proximity to the normal metal pads, or that a charge-imbalance effect at the S-N interface is responsible [3]. The measurable effects include the foot structure and an apparent lowering of the supercurrent at the device ends that creates two breakpoints in the "supercurrent" of the entire bridge when the temperature is not too far below Tc. Also, in many devices high output-noise peaks occur at high DC bias voltages (several mV), that can be attributed to the end effects if these can indeed be regarded as a lowering of Tc. According to this theory, the "Te-distribution" can sometimes intersect the "Tc-distribution" close to tangentially near the device ends, as in Fig.3 (case A). This means that a larger fraction of the device would be close to its "local Tc" than would be the case at surrounding bias points where the intersection occurs at a larger "non-tangential" angle. As a consequence, a larger amount of noise is generated at the specific bias point indicated in case A in Fig.3 . The height of the noise peak can be quite high even though only a fairly small part of the device is involved, since the dc bias current is high and since the amount of output noise is proportional to the square of that current. The interpretation is supported by the experimental observation that the noise peaks are shifted down to lower bias levels (and lower electron temperatures) if the ambient temperature is closer to the "Tc" of the foot structure, cases B and C in Fig.3 . The fact that the noise peaks in Fig.3 can be shifted down, points to a method that can potentially increase the conversion efficiency of a diffusion-cooled HEB mixer. The peaks are not useful for a low-noise mixer application when they occur at high voltages (Fig.3 Case A), since only the end points of the device would be close to Tc. The electron temperature at these endpoints cannot be modulated significantly by the signal and LO, since they are heat sunk directly to the contacts, which are held at a fixed (ambient) temperature. The conversion efficiency would therefore be very low. The situation is different in Case C, since the electron temperature is close to Tc also in regions inside the bridge where the electron temperature <u>can</u> be coherently modulated. This would suggest that an internal "Tc-distribution" with a parabolic shape would allow the electron temperature to be close to Tc in a larger part of the device. In reality it is not known what shape the effective Tc-distribution has in actual devices. The simplest analysis would be to represent the distribution by the shape of the R vs. T curve, but whether this is indeed physically justified remains to be determined. The device length would need to be used as a parameter in adjusting the shape of the Tc, and it would depend on how far into the device the end effects do extend. In this model the maximum supercurrent (Ic) should be a local parameter inside the device (similar to the description in [1]) and should depend both on the local electron temperature Te(x) and the "local transition temperature" Tc(x). A finite dc bias current is required to operate the device as a mixer, and in our model one condition for high conversion efficiency should therefore be that the local Ic(Te(x),Tc(x)) is close to this bias current in much of the device, rather than having direct agreement between Te(x) and Tc(x). In a way the situation resembles larger phonon-cooled HEB's that automatically have Te close to Tc in much of the device. Such phonon-cooled devices sometimes exhibit a "flat" segment in the IV-curve, which does indicate that much of the device has the same Ic. We have observed such a flat segment at 1.22 K in a 100 nm long diffusion-cooled Ta device with a Tc of about 2.5 K, Figs. 4 and 5, which indicates that this situation can indeed also be achieved in a diffusion-cooled device over a narrow ambient temperature range (less than 0.1 K in this case). As seen in Fig.5, the flat part of the IV curve also generates more noise, as expected from the described model.

In brief conclusion, by observing output noise from Ta diffusion-cooled HEB's we conclude that the suppression of Tc at the ends of a device can be used to achieve a constant Ic in a significant fraction of the device at a specific ambient temperature, if the device length is chosen correctly. If this situation can be achieved in an actual HEB mixer with LO power applied, the conversion efficiency would likely be increased since a larger part of the device could participate in the mixing process.

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References

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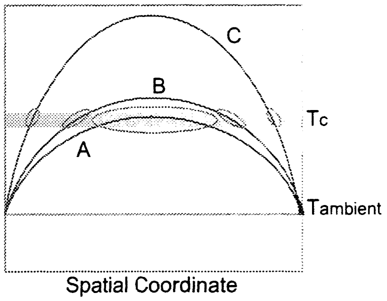

Fig.1; Internal temperature distributions for three different bias points (Fig.2)

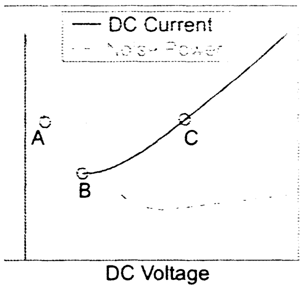

Fig.2; Schematic of an IV curve and of the microwave output noise.

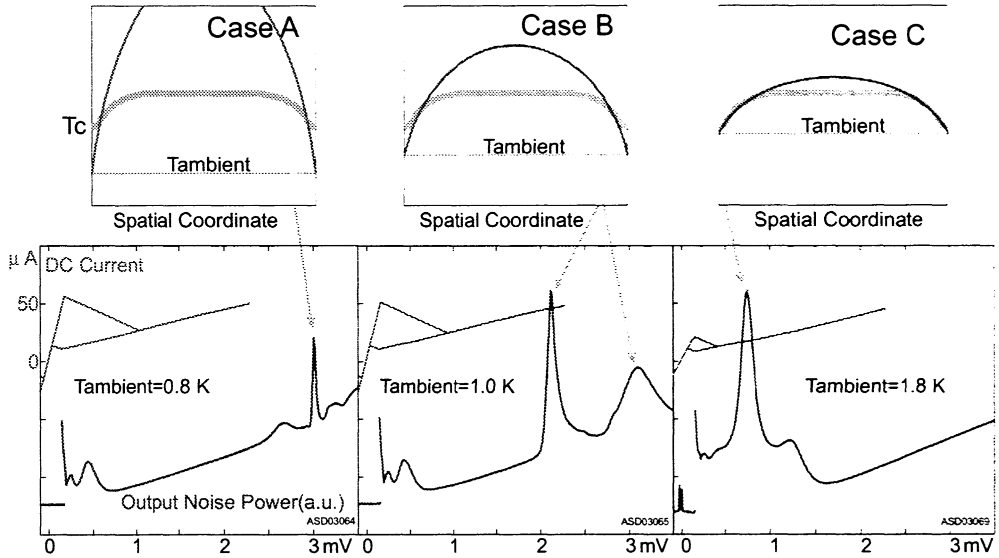

Fig.3; Measured IV curves and output noise at 1.5 GHz, measured with a 0.2 micron long Ta bolometer. The graphs of the internal temperature distributions are schematics only.

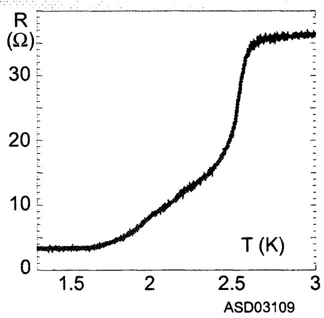

Fig.4; Resistance vs. Temperature curve for a 0.1 micron device.

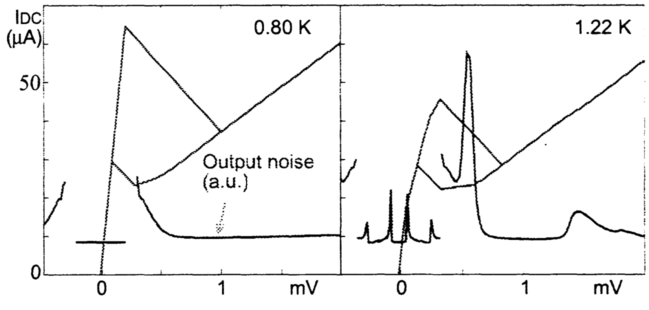

Fig.5; Measured IV curves and output noise at 1.5 GHz for the device in Fig.4 at two different temperatures.