Performance of a Superconducting Detector Circuit Using a Schottky Barrier Diode for Bandwidth Modulation.

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***Abstract*—This paper describes some operational characteristics, at microwave frequencies, of a detector consisting of a Schottky barrier diode, integrated within a superconducting thin-film YBCO matching circuit. Emphasis is placed on the practical, operational characteristics, rather than the (better understood) transport properties of the semiconductor. The temperature dependence of key characteristics is analysed and, in particular, the change of video bandwidth with decreasing temperature. Because the bandwidth is also a function of bias current, a novel means of controlling, optimising, or modulating the bandwidth is proposed. In a system application, an unwanted variation in bandwidth could result in either a decrease in tangential sensitivity, or loss of data rate, with a consequent degradation of performance. It is proposed and demonstrated that the application of a small forward bias to the diode can be used to vary this bandwidth: a feature which could be utilised in practice to adaptively modulate, or control, the sensitivity of a detector system.**

I. INTRODUCTION

In many potential microwave system and sub-system applications, involving the use of high-T_c superconductors, the necessity of cooling the superconducting circuitry can be turned to an advantage by extending the cooling to other functional sections. When such sections incorporate active devices such as diodes and transistors, then cooling may offer improvements in noise performance. In addition, lower conductor and dielectric losses may be obtained or, as is the case here, when the passive circuitry, surrounding a diode detector is of superconducting material, the matching circuit losses may be reduced.

Whilst the effect of temperature on the transport properties of semiconductor materials is well known, the overall performance of packaged devices of various types, together with associated RF circuitry, is less well documented. The purpose of this paper is to highlight the effect of cooling to cryogenic temperatures on the more practical and operational performance of the detector circuit. In particular, the effect of temperature on the video bandwidth is noted: a feature which, it is shown, could be used with bias to vary this bandwidth. Conventional methods would not have the off-setting effects of temperature on the bandwidth and might have to resort to more complex arrangements such as switched filtering.

The microwave detector consisted of a Schottky barrier diode integrated within a thin-film YBCO microstrip circuit on MgO substrate. The circuitry itself contained input RF matching and a low-pass video output. Particularly for wideband applications, a matching circuit may introduce several dB's of loss, which may could be reduced by the use of superconductors. The theoretical effects of temperature on the most important characteristics of the diode are considered and, in particular, the change in video (output) bandwidth.

Such detectors are used in systems applications such as channelised receivers; radar warning; radiometry; instrumentation. Detection sensitivity, together with the output data rate required, are dependent on the output bandwidth. Too wide a bandwidth will decrease the signal-to-noise level, whilst too small a bandwidth will degrade the output data, or information rate.

The video bandwidth is a function of the junction resistance of the Schottky diode which, in turn, is a function of diode temperature. In addition, this resistance may also be varied by a dc bias (and RF) current flowing through the junction. Suitable control of this bias current thus offers a means of optimising the bandwidth for particular output information rates.

II. DETECTOR CIRCUIT AND DIODE

A. Detector Circuit

The packaged diode was modeled as a junction resistance Rj, a junction capacitance Cj and a series contact resistance Rs. The package contributes a series inductance Lp and shunt capacitance Cp.

The complete detector circuit had the schematic form of Fig.1 where, in this case, the matching circuit consisted of distributed reactances formed by sections of YBCO transmission line. The video output from the diode was taken via a simple low-pass capacitor circuit of low-impedance transmission line.

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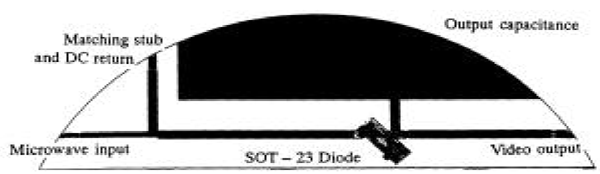

Fig. 1. Plan view of the YBCO detector circuit on MgO substrate with Schottky diode in style SOT-23 package.

B. Diode Temperature-dependent Characteristics

The junction resistance of the diode is a variable and depends both on the total current (microwave plus dc) flowing and on temperature, as in (1).

$$R_j = \frac{n\,k\,T}{q\,(I_s + I_b)} \qquad (1)$$

Here, n is an ideality factor determined by the manufacturing process; k is Boltzmann's constant (1.38 x 10^{-23} J/K); T is the absolute temperature, (Kelvin); q is the electronic charge (1.602x10^{-19} Coulomb); I_S is the reverse saturation current (Amp); and I_b is the applied dc bias current (Amp). The saturation current is, itself, a function of temperature and is given by [1]

$$I_s = I_{so}\left(\frac{T}{T_o}\right)^{\frac{2}{n}} \exp\left[-\frac{q\psi}{k}\left(\frac{1}{T}-\frac{1}{T_o}\right)\right] \qquad (2)$$

where V_b is the bias voltage and I_{so} is the saturation current at zero bias and ψ is the barrier potential.

C. Detector Characteristics

Two main detector characteristics [2], which are also dependent on the input and output circuitry of the diode are the voltage sensitivity (γ) and the tangential sensitivity (T_{SS}); both are also functions of temperature. The former is a measure of the output voltage from the detector for a given level of microwave input power. As such, γ depends upon the input matching and load circuits, in terms of both reflection coefficient and losses of the former and shunting effect of the latter. Voltage sensitivity is also a function of frequency as the decreasing reactance of C_j with increasing frequency shunts the junction resistance R_J. If γ_o is the open-circuit voltage sensitivity, then

$$\gamma = \frac{\gamma_o}{1 + \omega^2\, C_j^{\,2}\, R_s R_j} \qquad (3)$$

for the case when the load resistance, $R_L >> R_J$. For values of load resistance comparable with R_J, then γ_o would be degraded by the factor $R_L/(R_J+R_L)$.

The condition for tangential sensitivity is given by

$$T_{SS} = \frac{2\sqrt{2}}{\gamma} Vn \qquad (4)$$

V_n is the total noise voltage from the detector, consisting of shot noise, thermal noise and amplifier noise from the load where:

V_n=

$$T\sqrt{4kTB}\left[\sqrt{\frac{Rs}{To}} + \sqrt{\frac{kn}{2qIb}\left(1+\frac{Is}{Is+Ib}\right)} + \sqrt{Ra}\right] \qquad (5)$$

R_a is the equivalent noise resistance of the load.

Equation (5) predicts a lower value of T_{SS} with lower temperature and would be a system advantage of cooling.

Finally, and of interest here is the output, or video, bandwidth of the detector circuit as a function of temperature. The bandwidth is defined as the 3 dB cut-off point of the output low-pass filter circuit and is given by

$$B = \frac{(R_j + R_L)}{2\pi\, C_T\, R_j\, R_L} \qquad (6)$$

where C_T is the total output capacitance of diode and load.

Thus, for the case of $R_j << R_L$, it can be seen from (6) that the detection bandwidth varies inversely with the diode junction resistance which, in turn, is a function of temperature (1). It may also be noted, from (4) and (5) that the tangential sensitivity varies as the square root of bandwidth. The exact way, however, in which R_j and B vary with temperature depends on the structure of the diode and the level of saturation current.

Schottky barrier diodes fall into two broad categories of zero bias and externally biased types [3]. The former, normally of p-type silicon has values of I_s on the order of microamps, i.e. comparable with typical bias currents, whilst the externally biased diodes, normally n-type silicon, have saturation currents on the order of nanoamps. Equation (1) thus illustrates two possibilities, depending on the particular type of diode.

For the zero bias diode, $I_b = 0$ and R_j increases rapidly with decreasing temperature as I_s decreases. Consequently, the video bandwidth will decrease, thereby reducing the output data rate possible from the detector [4]. However, with an external bias applied, this will only be the case over a limited temperature range as, with R_j increasing exponentially, the bandwidth will eventually become defined only by R_L and the above process will reverse, i.e. R_J decreasing and bandwidth increasing. This situation is shown in Fig. 2 for several values of bias current, as

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computed from the SPICE data of Table 1.

TABLE I
SPICE MODELS FOR TWO SCHOTTKY DIODES

Property	HSMS 2850 Zero-bias	HSMS2860 External bias
C_P (pF)	0.08	0.08
L_P (nH)	2	2
R_S (ohm)	25	5
N	1.06	1.08
I_{SO} (amp)	3×10^{-6}	5×10^{-8}
ψ (eV)	0.69	0.69

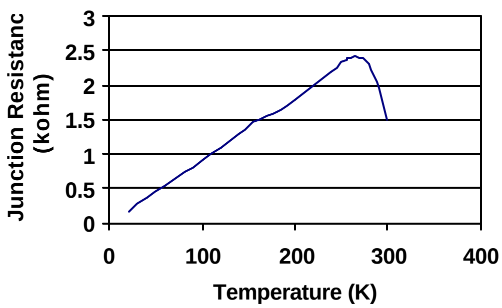

Fig. 2. Variation of junction resistance with temperature for the HSMS 2850 diode at a bias current of 10 microamp.

On the other hand, externally biased diodes have forward bias currents on the order of microamps so that, in comparison, I_s is negligible and R_j decreases with temperature, whilst the bandwidth increases. Such an increase in bandwidth would decrease the output signal-to-noise ratio of the detector by decreasing the tangential sensitivity.

Thus, at cryogenic temperatures, both types of diode will behave in similar fashion with temperature and bias, allowing direct control of the output bandwidth and bias current alone.

Shown in Fig.3 is the variation in bandwidth with temperature, for the externally biased diode. Fig. 4 shows the corresponding variation of bandwidth with bias current at 77K.

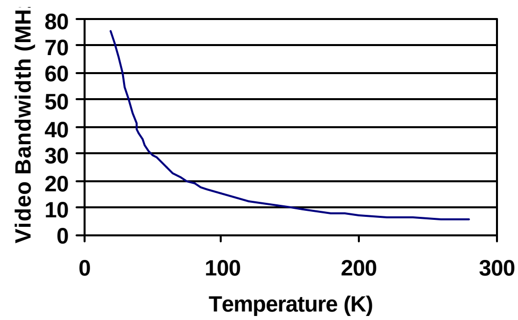

Fig. 3. Variation of video bandwidth with temperature the HSMS 2860 diode at a bias current of 100 μ amp.

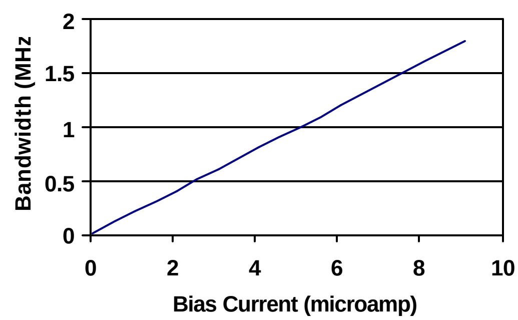

Fig. 4. Calculated variation of video bandwidth with bias current at 77 K (applicable to both types of diode).

III. EXPERIMENTAL

A basic detector circuit, in microstrip transmission line, was fabricated in thin-film YBCO on 0.5 mm MgO substrate and a plan view is shown in Fig. 3. The superconductor film thickness was 200 – 230 nm and T_C was 87K; the pattern being wet-etched. A gold ground plane was sputtered onto the substrate, as were silver contacts to the YBCO conductor, for RF and DC connections. A similar circuit was also fabricated on conventional microstrip RT/Duroid 6010 substrate board. This board had a dielectric constant of 10.5, comparable to that of the MgO and also had a similar thickness of 0.6 mm; circuit and ground plane were of copper. Previous work [5] had determined the change in dielectric constant and expansion of this material over the 10 K to 300 K temperature range.

The relatively high diode impedance was matched using the series transformation of a section of transmission line to match the real part of the impedance, followed by a short-circuited section to match the reactive part. This latter element also served as the DC return path for the diode. The operational frequency was 1000 MHz.

For operation at low-temperature, the circuits were immersed in liquid nitrogen and tests were carried out at 77 K. The video (output) bandwidth was determined by applying a fast risetime (10 ns) RF pulse at the input and observing the decremental decay of output voltage.

At both room temperature and 77 K, the normal conductor circuit exhibited a relatively wide RF input 3 dB bandwidth between 500 MHz to 2.4 GHz. On the other hand, the input bandwidth of the YBCO circuit was reduced to 112 MHz, centered at 1186 MHz, indicating an increase in Q-factor and lower losses of the input matching circuit. The normal conductor circuit at room temperature had a square law voltage sensitivity on the order of mV's per microwatt but, at 77 K, the output voltage of both normal and superconducting circuits reduced by up to a factor of 5. Such a change was attributed to the fact that, for a given input power level, the detector output voltage is a function of temperature and peaks at an optimum value.

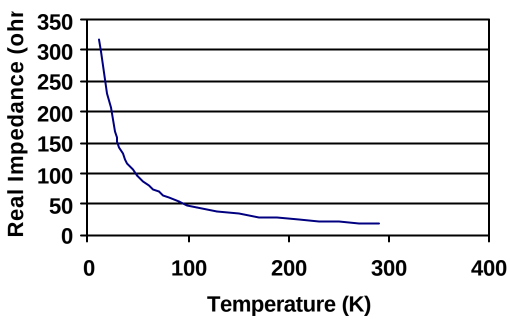

Fig. 5. Variation of the real part of diode input impedance with temperature for the HSMS 2850.

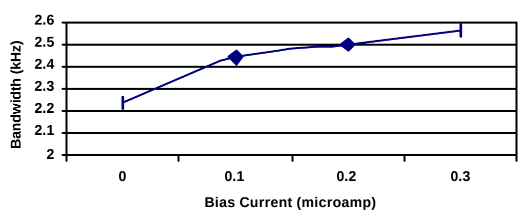

Fig. 6. Measured variation of video bandwidth with bias current for the HSMS 2850 diode at a temperature of 77 K.

The diode input impedance would also be expected to vary with temperature, thus altering the input match. However, as shown in Fig. 5, the real component is close to 50 Ù at 77 K; the reactive component suffers little change.

With external bias applied at 77 K, the video bandwidth of the superconducting detector could be varied by approximately 1% over a bias current of 0-0.3 microamp and is shown in Fig. 6. Output voltage also decreases, as might be expected, due to the corresponding reduction in R_j and its effect of shunting the diode junction.

IV. CONCLUSION

Some key parameters of the Schottky barrier diode have been examined and their temperature dependence analysed. In this paper, attention has focussed on the variation of video bandwidth of a detector circuit with temperature. It is suggested that this variation could be utilised for bandwidth modulation or optimisation. A simple YBCO superconducting detector circuit was fabricated on MgO and limited control of bandwidth by bias current was demonstrated. Considerable further work is necessary to evaluate and optimise such parameters as diode input impedance and reflection coefficient; voltage and tangential sensitivity; input bandwidth and the effects of cooling to cryogenic temperatures.

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