Design and operational considerations for robust planar GaAs varactors: A reliability study

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Abstract **— Fix-tuned, broadband local oscillator (LO) sources to 1900 GHz have been developed for the HIFI instrument on the Herschel Space Observatory. Each LO chain consists of cascaded multipliers (doublers or triplers) being pumped with high-power (>100 mW) power amplifier modules in the 70 to 110 GHz frequency range. For long-term mission reliability it is important to quantify the safe operating conditions for these multipliers, especially when pumped with high input power. This paper will describe on-going investigations into the effects of excessive reverse currents in Schottky diodes along with presenting a methodology for determining safe bias conditions for a given multiplier.**

I. INTRODUCTION

In recent years tremendous progress has been made in demonstrating broadband all planar solid-state LO chains to 1.9 THz [1,2,3] for the heterodyne instrument on the Herschel Space Observatory [4]. In order to produce sufficient output power at frequencies above 1 THz, the first stage multipliers are being pumped with power levels of more than 100 mW at W-band with power-combined GaAs based power amplifiers [5]. The multipliers must be designed and operated keeping this high RF input power requirement in mind. Though there have been some general studies regarding the reliability of GaAs Schottky diodes [6,7,8] we are not aware of any systematic study on the reliability of planar high power GaAs varactors. The situation is further complicated due to the fact that reliability of the devices is intimately dependent on the fabrication technology as well as the RF design. The goal of the present study is to determine what constitutes a safe RF and bias range for a given multiplier.

II. ELECTRICAL STRESS

Excessive amounts of either forward or reverse currents can cause the GaAs/metal contact to degrade. Catastrophic failure of GaAs Schottky contacts with forward current of 14mA/μm^2 has been reported in [8] for whisker-contacted diodes. For planar diodes it is observed that the forward current limit is often imposed by the metal trace connecting the anode (diode finger), which acts as a fuse. However, the effect of reverse currents on diode characteristics is more difficult to predict. In the presence of constant reverse currents we have observed the diode bias voltage at constant current degrade even before there is avalanche breakdown at room temperature.

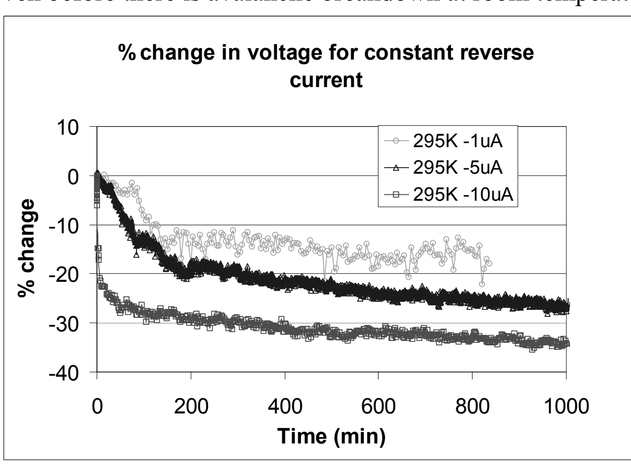
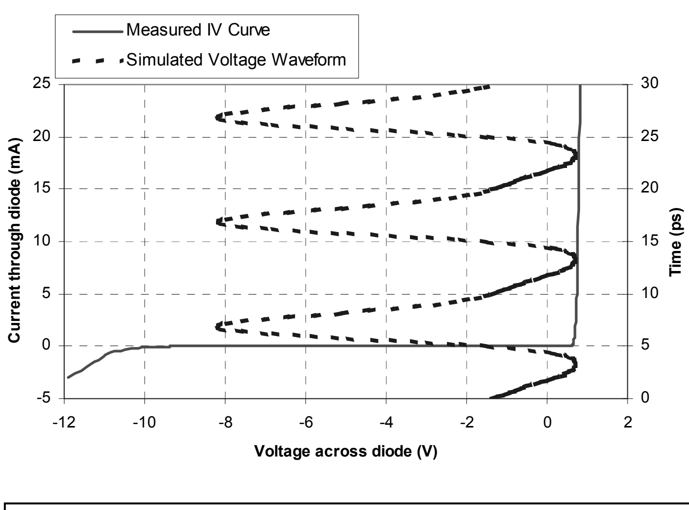


Figure 1: Measured reverse bias voltage for constant reverse currents of -1μA, -5μA, and -10μA. The diodes used have anode areas of 1.5 μm^2 with $2*10^{17}$ cm^{-3} doping.

Degradation of the Schottky contact due to reverse current is investigated by passing a constant reverse current through a device while monitoring the required voltage over an extended period of time. This is depicted for three different current levels at room temperature in Figure 1. The anode area is 1.5 μm^2 and thus the current densities are 0.67 μA/μm^2 for -1 μA, 3.3 μA/μm^2 for -5 μA, and 6.7 μA/μm^2 for -10 μA. The measurements at –1μA are more scattered than the others due to the low current but it follows the trend indicating that lower reverse currents do not result in as severe of degradation as higher reverse currents. However, it is clear that even at -1 μA of reverse bias current, the reverse voltage will gradually degrade. For all three current values, the reverse voltage approaches a fixed value after a few hundred minutes. Similar fixed-current reverse voltage behavior with time is observed when high RF power is applied. Furthermore, the degradation occurs at lower negative bias voltages, indicating as one would expect that the RF input power aggravates the reverse current damage to the device. The rate of degradation is expected to depend on the reverse current amplitude, RF power, device doping, operating frequency and device technology. These effects will be measured quantitatively in the future.

III. DIODE CURRENTS IN THE PRESENCE OF RF POWER

To better understand appropriate bias conditions for a varactor it is essential to investigate the RF induced current and voltage waveform on the diodes. This can be done by analyzing the circuit iteratively with harmonic balance code [9,11, 11]. The solid line in Figure 2 represents a measured I(V) curve for a 3x12 μm^2 anode with 2*10^{17} cm^{-3} n carrier concentration. This anode is part of a 200 GHz balanced doubler chip, which has three such anodes in series and two parallel branches for a total of six anodes. During the circuit simulation, the bias voltage is optimized at each frequency to maximize the RF output power. However, it is obvious that the bias voltage must not exceed a certain range in order to avoid excessive currents in the positive or reverse directions. In the presence of RF input power, a voltage is induced on the device. The voltage waveform is shown as a dashed line in Figure 2. This waveform is simulated for an input power of 25 mW/anode and the anode biased with –2.5 Volts. The breakdown voltage V_{br}, which is for the purposes of this paper defined as reverse bias voltage necessary to produce –10 μA of reverse current, for the single anode is measured to be -9.1 Volts. The shape of the induced RF swing depends on the embedding impedance of the multiplier circuit, the input power level, the frequency, and the bias voltage. The sinusoidal RF swing gets deformed due to the non-linearity of the device. The peaks of the voltage swing cannot be measured directly; only measurements of the average voltage and current are possible at these frequencies.



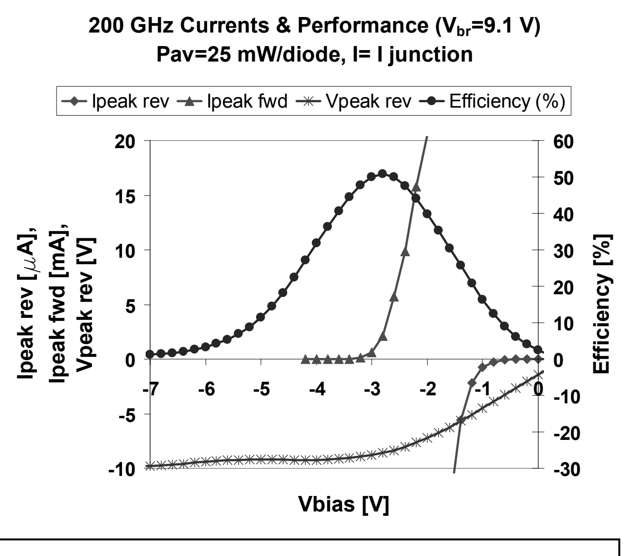


Figure 2: 200 GHz doubler anode (3x12 μm^2 anodes and 2*10^{17} cm^{-3} doping). The I(V) curve was measured at 295 K on a single diode. The voltage waveform is calculated (295 K) for a single diode with 25 mW input power per diode (150 mW total) biased at -2.5 V per anode (-7.5 V total).

Figure 3: Simulation of the current and voltage at 295 K induced in a single diode of a balanced varactor doubler with 25 mW per diode input power at 100 GHz. The calculated peak currents and the efficiency are displayed as a function of bias voltage (Vbias).

Along with the voltage waveform, it is also important to study currents in the device while RF power is present. Such a simulation for a fixed input frequency of 100 GHz, is shown in Figure 3. As the bias voltage (Vbias) is swept from positive towards negative, a sharp increase in the peak reverse current (Ipeak rev) is observed. Even when biased at only 20 percent of the breakdown voltage V_{br}, the peak reverse voltage (Vpeak rev) swings close to the breakdown voltage. Though the maximum efficiency based on this simulation alone would require a bias voltage of about 0.28 V_{br} this would clearly be courting danger. In practice, such a diode should be biased close to 0.15 to 0.18 of V_{br} in order to avoid excessive reverse currents, which can lead to device failure. One should use caution in interpreting this plot since it does not include the temperature and frequency dependence. Moreover, due to the lack of a satisfactory model for predicting the reverse currents through Schottky diodes it is believed that the predicted currents are somewhat higher than what actually occurs in the laboratory. These current simulations are probably pessimistic [9], since I(V) measurements indicate that it overestimates the reverse current by about an order of magnitude. The rise in peak reverse current therefore probably occurs at more negative bias voltages than plotted in Figure 3. Simulations like these along with empirical results are both needed to determine safe and useable bias limits for these particular multipliers.

IV. PROPOSED METHOD FOR THE EXPERIMENTAL DETERMINATION OF BIAS LIMITS

Since the direct measurement of the peak reverse current is not possible, the following measurements were made to determine the safe operating conditions of a 200 GHz doubler. At a fixed frequency, the input RF power was increased from 10 mW to 170 mW in 10 mW steps. At each input power the bias voltage was recorded at four different bias currents. First, the bias was adjusted to obtain maximum output power. Second, the bias was adjusted to obtain +7 mA bias current. Third, the bias was adjusted to obtain +0 mA through the device. Finally the bias was adjusted to give –5 μA through the device. These measurements are shown in Figure 4a. The forward current at this level poses no risk to the device and is below 1 mA/μm^2 current density. However, reverse current of –5 μA will be detrimental to the device and thus the safe bias voltage limit must be more positive. Figure 4b shows the estimated safe operating zone for this particular multiplier and for this particular frequency. The –5 μA bias line is de-rated to 75% to provide a safer operating condition. The dashed trapezoid in this figure indicates the approximate safe operating bias zone for this device.

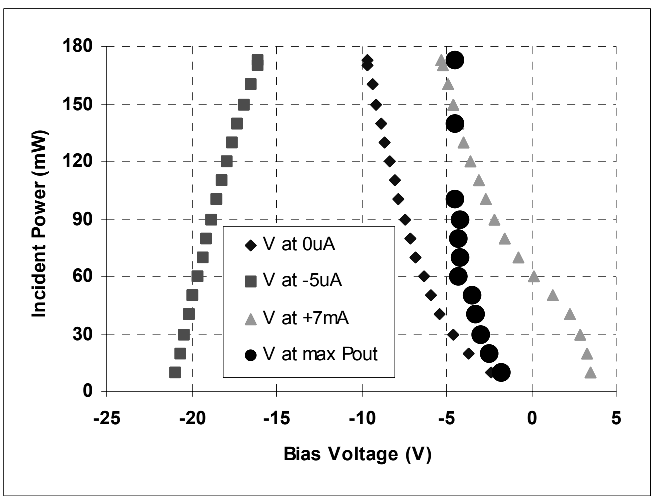


Figure 4a: 200 GHz doubler with six 3x12 μm^2 anodes and $2*10^{17}$ cm^{-3} n carrier concentration. Measurement of bias voltage for various bias currents and RF input powers.

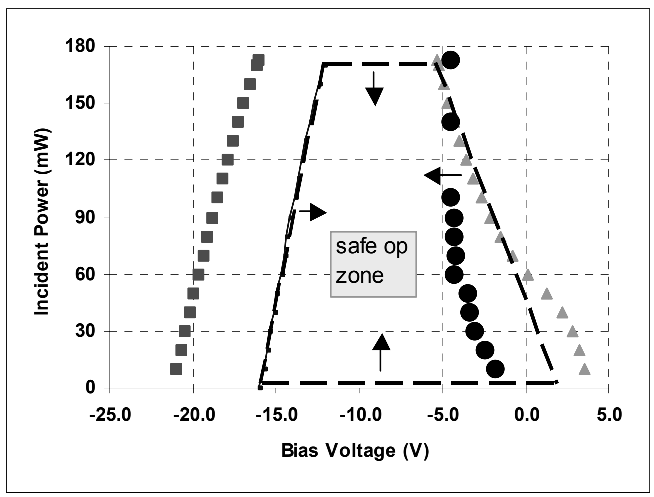


Figure 4b: Definition of safe operational range. The maximum safe RF input power is limited by the design specification of the thermal dissipation.

V. CONCLUSION

Reverse currents through Schottky diodes can degrade the breakdown voltage thus ultimately leading to device performance failure. The amplitude of the current along with the device technology will determine how long it takes for catastrophic failure. A preliminary procedure for determining safe operating conditions for a given multiplier has been outlined in this paper. A quantitative approach is under development that will be based both on simulated and experimental behaviors and will define safe operating bias conditions for any given multiplier.

VI. ACKNOWLEDGEMENTS

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