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Low frequency noise performance of quantum tunneling Sb-heterostructure millimeter wave diodes

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Abstract. Sb-heterostructure quantum tunneling diodes, fabricated from epitaxial layers of InAs and AlGaSb, are a recently proposed device for RF direct detection and mixing in the submillimeter wavelength range. These diodes exhibit especially high nonlinearity in the current-voltage characteristic that produces the rectification or mixing without bias. This is a highly desirable feature as the device does not suffer from large $1/f$ noise, a major shortcoming in other devices such as Schottky barrier diodes or resistive room temperature bolometers. In this paper we present the noise characteristics of the diode as a function of the bias voltage. At room temperature and zero bias, the device demonstrates a Johnson noise limited matched noise equivalent power of 1 pW/Hz$^{1/2}$.

INTRODUCTION

At present, millimeter wave imaging focal plane arrays are based on microwave monolithic integrated circuits (MMICs), and their pixel count is limited by the complexity and cost of the components and assembly. Moreover, the maximum operation frequency is limited by the availability of low noise amplifiers to <200 GHz. Bolometers can provide a low cost alternative and cover frequencies up to the infrared albeit with lower sensitivity [1] . Schottky diodes, the workhorse technology for high frequency mixers also can operate as direct detectors up to several THz, though typically displaying an RC -limited rolloff above a few hundred GHz. Their great drawback has been $1/f$ noise, brought about by the DC bias required for sufficient non-linearity of the I-V curve. In this paper we present the $1/f$ noise performance of a novel direct detector, the InAs/AlSb/GaSb heterostructure backward diode [2] The special feature of these diodes is that they exhibit highly non-linear current versus voltage characteristics near zero bias. In the ideal case, the absence of DC bias means that the devices do not suffer from $1/f$ noise. These properties are highly attractive for arrays of direct detectors for millimeter wave imaging.

DIODE $I(V)$ & NOISE MEASUREMENTS

Details on the fabrication can be found elsewhere [3]. Summarizing, the InAs/AlSb/GaSb tunnel diode layers are deposited using molecular beam epitaxy on semi-insulating GaAs substrates, using an InAs buffer layer process. The InAs layer is followed by a 2000 Å thick GaSb anode, 200 Å of undoped AlGaSb, a 32 Å thick undoped AlSb tunnel barrier, a 500 Å thick InAs cathode, and finally a n$^+$ InAs contact layer. Three diodes with a junction area of 2 μm × 2 μm were characterized by first measuring their DC $I(V)$ characteristics, while monitoring the differential conductance dI/dV and its derivative d^2I/dV^2 using lock-in technique. The measured $I(V)$ and dI/dV are shown in Fig 1. At $V = 0$, the three diodes had a mean junction resistance of $\overline{R}_j = (14.4 \pm 0.1\ \mathrm{k\Omega})$. The current responsivity (or curvature) of the diode is given by $\gamma = (d^2I/dV^2)/(dI/dV)$, and for the three measured diodes we obtained a mean curvature of 39.5 A/W at zero bias. A measured $\gamma(V)$ for one diode is shown in the inset of Fig. 1. The divergences at 43 mV and at 111 mV correspond to the points where dI/dV crosses zero.

Measurements of the diodes' noise can be used in combination with the $I(V)$ measurements to determine the true figure of merit for a direct detector, the noise equivalent power (NEP). The diode was again biased in series with the 10 kΩ current sensing resistor R_L using a programmable battery power supply. As the rectified RF power will produce a small positive voltage across the device, we concentrate on the noise on positive bias. The voltage noise spectral densities at two bias voltages are shown in Fig. 2. At $V = 0$ the noise corresponds to the Johnson noise of the junction resistance R_j. At finite values of V the $1/f$ and shot noise appears. To quantify the $1/f$ noise, each spectrum was fit with a voltage noise

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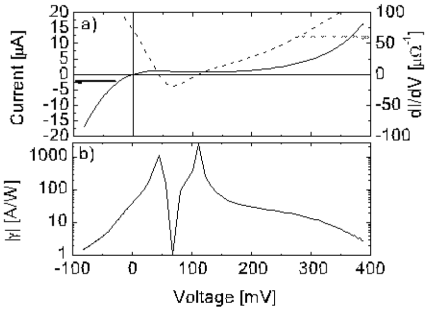

FIGURE 1. a)The $I(V)$ characteristics of the diode with the dI/dV curve as a function of the bias voltage. b) The absolute value of the current responsivity $\gamma(V)$.

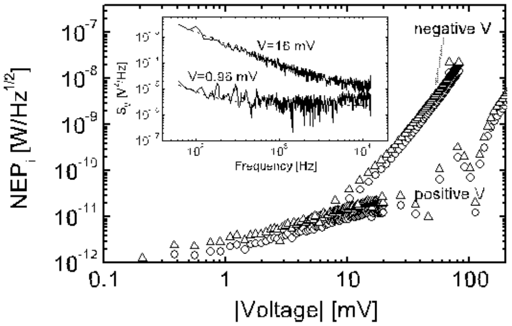

FIGURE 2. The matched (circles) and unmatched (triangles) NEP of a diode as a function of the absolute value of dc bias. The minimum NEP is obtained at $V \to 0$ due to the rapid increase in $1/f$ noise which overcomes the increase in the responsivity at small positive bias. The inset shows noise spectra recorded at V=0.96 mV and V=16 mV. The dashed lines indicate the fits to the spectra.

power spectral density given by $S_{\mathrm{fit}} = \alpha V^m/f^r + v_n^2$, where the white noise term v_n includes contributions from the Johnson noise and the shot noise. For the three diodes, the mean fitted values yielded $\alpha = 3.18 \cdot 10^{-6}$ $\mathrm{V}^{2-m}\mathrm{Hz}^{r-1}$, $m = 2.58$ and $r = 1.33$. The fact that the scaling with voltage deviates from that of the usual V^2 scaling is not surprising, as this strictly holds for uniform conductors at thermal equilibrium [4]. Even though the $1/f$ noise does not directly effect the NEP at zero bias, it should be noted that it does have an effect on the dynamic range of the device. The origin of the $1/f$ noise in our diodes is likely due to a similar scenario as that described in Ref. [5], according to which thermally excited traps states modulate the barrier height and thus its transmission coefficient. A noteworthy property of the tunnel diodes (with a series resistance $R_s = 17.6\,\Omega$ in series with the parallel combination of R_j and $C_j = 13.6$ fF) is that C_j fF is only weakly dependent of voltage [6]. In the case of zero bandwidth, when operated at zero bias, and at $\omega_c/2\pi \gg (R_j R_s C_j^2)^{-1/2} \approx 23$ GHz, the voltage responsivity yields with the given junction parameters $\mathcal{R}_{V0} \approx 16$ V/mW , with the noise given by the Johnson noise of R_j yielding $\mathrm{NEP}_m|_{\Delta\omega\to 0} \approx \sqrt{16 k_B T R_j}\,\omega_c^2 C_j^2 R_s/\gamma \approx 1$ pW/$\sqrt{\mathrm{Hz}}$ at $\omega_c/2\pi = 95$ GHz. Taking into account reflection loss only, the unmatched NEP is given by $\mathrm{NEP}_u = \mathrm{NEP}_m/(1-|\Gamma|^2)$ where Γ is the reflection coefficient. For example, when connected to a 100 Ω load, $\mathrm{NEP}_u = 3.7$ pW/$\sqrt{\mathrm{Hz}}$. As a comparison, room temperature antenna coupled microbolometers can reach a $\mathrm{NEP}_m \approx 10$ pW/$\sqrt{\mathrm{Hz}}$, but only at a modulation frequency of 50 kHz [7]. It should be noted that due to their purely real impedance, bolometers can be easily matched and have an matched NEP that is independent of operating frequency.

CONCLUSIONS

The measured the noise properties of the zero bias quantum tunneling diodes show that these non-optimized devices have already reached a sensitivity that challenges other existing room temperature detectors in this wavelength range. The high sensitivity, low cost and reproducibility of the diodes make them an attractive newcomer to the millimeter and submillimeter wave detector arena.

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