Improved Millimeter-Wave Mixer Performance Analysis at Cryogenic Temperatures

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Abstract—**The results are presented of a 600-GHz mixer performance analysis using an improved model for computing the Schottky diode capacitance-voltage (C-V) relationship. The computed C-V data for a realistic submillimeter-waver mixer diode are given as a function of physical temperature and compared to the standard analytic expression based on a solution of Poisson's equation. Both C-V relationships are used to predict the performance of an ideally terminated 600 GHz mixer operating at 300, 140, 80, and 30 K. It is shown that the drift-diffusion model more accurately describes the mixer performance when the physical temperature is reduced below ≈ 100 K.**

I. Introduction

It has been known for some time [1] that lowering the physical temperature of a GaAs Schottky barrier mixer diode reduces the intrinsic noise. The realizable improvement in sensitivity depends in a complicated way on the specific electrical properties of the diode. At millimeter-wave frequencies (100–300 GHz) reductions in overall mixer noise temperature of two to three times are typical in cooling from 300 K to 20 K [2] and factors as high as four times have been reported [3]. However, extrapolation to submillimeter wavelengths must be made cautiously as current diode technology does not allow direct scaling of physical parameters beyond a few hundred gigahertz. In an effort to determine whether or not there would be a similar improvement in mixer performance with decreasing temperature at submillimeter wavelengths we attempted an analysis of a realistic mixer diode in an idealized embedding environment. In so doing we found significant disagreement between the predicted and measured improvement in mixer performance as a function of physical temperature [4]. This discrepancy was due in large part to the capacitance-voltage relationship being used in the analysis and is the concern of this letter.

II. Capacitance Model

Computer analyses such as [5] can be used to accurately predict the performance of millimeter-wave Schottky barrier diode mixers and frequency multipliers over a wide range of operating conditions. However, these analyses are predicated on an accurate equivalent circuit for the nonlinear element and, in the case of Schottky diode mixers, on knowing the current and capacitance over the full range of instantaneous junction voltages. The diode current-voltage (I-V) relationship can usually be measured fairly accurately over the voltage range of interest and analyses based on the standard thermionic emission equations seem to correlate well with measured mixer performance up to several hundred GHz [5]. On the other hand, the diode C-V relationship is more difficult to measure, especially in regions of substantial forward conduction, and the usual analytic expression for the diode capacitance variation [6] approaches infinity when the applied voltage approaches the flatband condition, $V \geq \phi_b$, the barrier height. In room temperature mixers the flatband voltage is generally exceeded only under nonoptimal mixer operating conditions (higher than minimum noise) such as when the diode is pumped excessively hard or biased well beyond the turn on voltage knee. However at cryogenic temperatures the flatbound voltage is almost always exceeded when operating at the predicted noise minimum [4]. In addition, the relative importance of the diode capacitance in determining the overall mixer performance increases in the submillimeter-wavebands where the diode geometry limits the minimum capacitance to values somewhat higher than those obtained by directly scaling optimal lower frequency designs.

A more accurate model of the diode capacitance-voltage relationship can be obtained using a numerical technique that calculates directly the derivative of the charge with respect to voltage in the device. In this quasi-static calculation, Poisson's equation and the current continuity equations based on the drift-diffusion approximation are solved as a function of time until a dc solution is obtained. Such a technique has been reported upon elsewhere [7], [8]. Typical C-V curves as functions of diode physical temperature calculated using the drift-diffusion equations are compared with those obtained using the analytic expression $C(V) = C_{j0}/(1 - V/\phi_b)^{1/2}$ (C_{j0} = capacitance at zero volts) in Fig. 1 using data from a realistic submillimeter-wave GaAs Schottky barrier diode[1]. The trends predicted by the numerical calculations show some interesting behavior that we intend to discuss in a subsequent publication.

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[1] The diode chosen for this study was a UVa type 1H30-150. Measured physical data versus temperature were kindly provided by Dr. Tom Crowe of the University of Virginia Semiconductor Device Laboratory. This data is reproduced in Table I.

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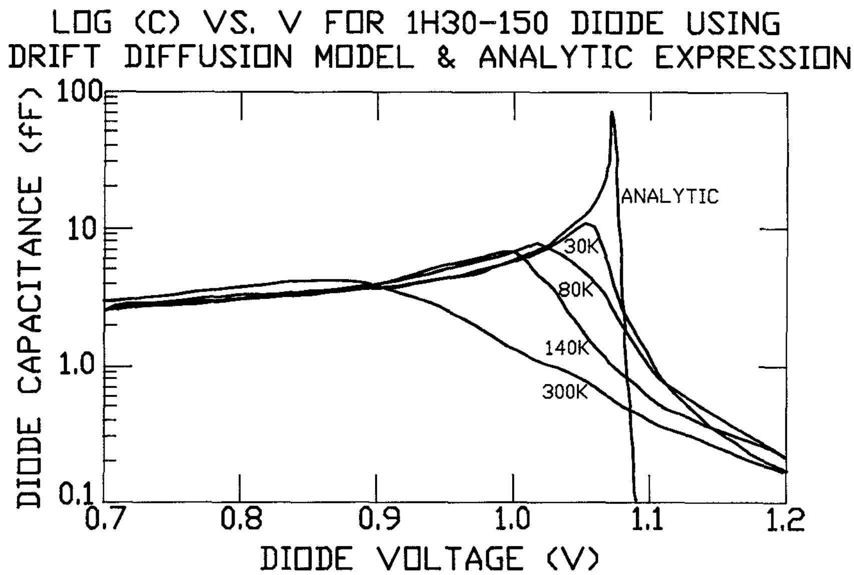

Fig. 1. Computed C-V for a University of Virginia (UVa) 1H30-150 diode using a drift-diffusion model. Analytical C-V relationship is shown for comparison.

TABLE I
UVA TYPE 1H30-150 DIODE PROPERTIES AND CALCULATED 600 GHz MIXER PERFORMANCE AS A FUNCTION OF PHYSICAL TEMPERATURE*

Diode Property	300 K	140 K	80 K	30 K
Capacitance, C_{j0}(fF)	1.5	1.5	1.5	1.5
Series Resistance, $R_s(\Omega)$	24	31	37	37
Ideality factor, η	1.11	1.28	1.66	3.86
Barrier height, ϕ_b(V)	1.04	1.07	1.07	1.07
Saturation Current, $I_s(A)$	1×10^{-17}	1.7×10^{-32}	1.4×10^{-43}	5.6×10^{-50}
Cutoff (THz), $1/2\pi R_s C_{j0}$	4.4	3.4	2.9	2.9
Mixer Performance	**300 K**	**140 K**	**80 K**	**30 K**
Total Mixer Noise (SSB)	662	564	417	340
Conversion Loss, dB (SSB)	6	6	6	7
Opt. RF Embedding Imped.	$89 + j62$	$90 + j63$	$94 + j66$	$89 + j59$
IF Output Impedance	$205 - j6$	$210 - j7$	$222 - j8$	$181 - j5$
Opt. Voltage Bias (V)	0.70	0.80	0.85	0.90
Opt. Current Bias (mA)	2.5	3.0	3.0	3.0
Required LO Power (mW)	1.6	2.2	2.3	2.4

*Diode epi layer is 1.2 μm and doped to 1×10^{17} cm^{-3}. Area = 1.96×10^{-9} cm^2. Mixer IF is 10 GHz. Analysis assumes ideal 3 port mixer with equal terminations at signal, image and LO frequencies and short circuits at the higher harmonics.

III. Computed Mixer Performance

The capacitance-voltage curves of Fig. 1 and the measured diode I-V parameters (Table I) were incorporated into a mixer analysis program [5] and the noise performance of a single diode fundamental mixer operating at 600 GHz was computed over a wide variety of bias and local oscillator (LO) power levels and physical temperatures. The analysis assumes an ideal three port mixer with optimal and equal signal and image terminations and all higher harmonics short circuited outside the diode series resistance. The input embedding impedance, bias and local oscillator power level have been varied to achieve lowest noise. High-frequency transport effects, hot electron and scattering noise, diode heating and voltage dependent series resistance have not been taken into account in the analysis.

The results of the mixer analysis are plotted in Fig. 2 along with those of an identical study using the analytic expression for the capacitance but with an upper limit of 50 C_{j0} below flatband and an abrupt transition to $C_{j0}/1000$ above flatband. Table I gives additional numeric results.

III. Discussion

Fig. 2 clearly shows the erroneous trend predicted by the analytic expression for the capacitance as the temperature drops below 100 K. This is caused by unrealistically high values for the average diode capacitance over an LO cycle as the voltage waveform approaches and finally exceeds the flatband condition. A more complete discussion is given in [4]. The drift-diffusion model predicts a continual decrease in total noise with physical temperature. The trend is corroborated by measurement results on similar diodes[2] although the predicted noise temperature and conversion loss are substantially lower than that actually obtained at these frequencies.

[2] Dr. N. R. Erickson at the University of Massachusetts has measured the receiver noise temperature of a single diode second harmonic mixer operating at 650 GHz as the physical temperature was lowered from 300 to 100 K. This mixer had a UVa type 1E13 diode with R_s = 17 Ohms and C_{j0} = 1.5 fF at 300 K. The single sideband receiver noise temperature went from 6000 K at 300 degrees to 3520 K at 150 degrees to 3040 K at 100 degrees. The overall receiver noise decreased by a factor of ≈ 1.7 over this temperature range for a similar diode operating in a fundamental mixer mode.

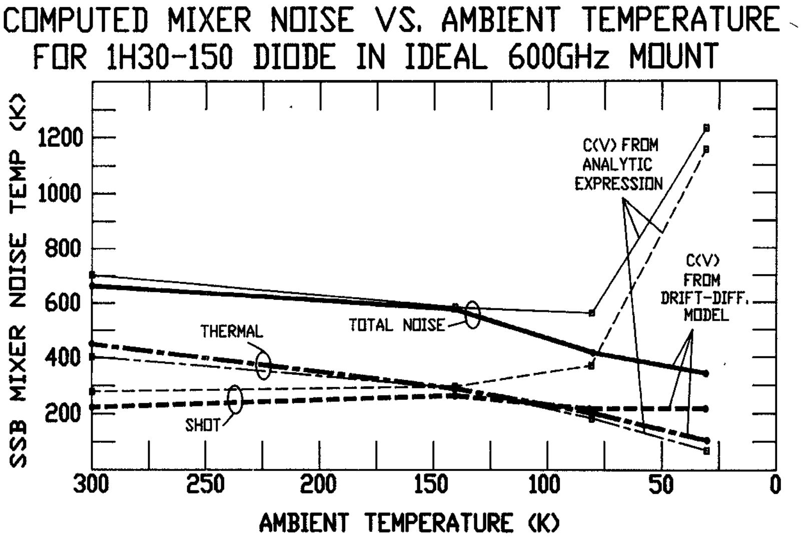

Fig. 2. Calculated single sideband mixer noise temperature as a function of physical temperature for a UVa type 1H30 diode at 600 GHz using the analytic expression and drift-diffusion model for the C-V relationship.

This is due in part to the omission of hot electron noise [9] in the present analysis.

Some of the analysis results are puzzling and deserve mention. First, the predicted improvement in noise performance from 300 to 80 K is not as great as one obtains experimentally at these frequencies. Second, the analysis predicts that both the optimal bias current and the required LO power level do not decrease with physical temperature even though the diode I-V curve has sharpened substantially. Both of these predicted results fall in line with measurements when the diode dc series resistance is kept constant with temperature rather than being allowed to increase as indicated in Table I. There has been a suggestion [10] that this is in fact a more accurate model and that the values of $R_s(T)$ in Table I are artifically high due to an inability to measure the actual diode epitaxial and substrate resistance independently of the junction resistance itself.

Although we have made some progress on understanding the relationship between capacitance and mixer performance further improvements clearly are required in our diode model as we move towards higher frequencies and lower temperatures.

IV. Summary

A more accurate model of the capacitance of a Schottky barrier diode in the large forward current regime has been used to obtain an assessment of the improvement to be expected from submillimeter-wave mixers upon cooling. The results show 1) the increased importance of the diode capacitance at low temperatures, 2) the necessity for using an accurate model for the capacitance variation with voltage in regions of large forward conduction, and 3) improved agreement between the predicted and measured performance with decreasing temperature for a realistic diode at submillimeter wavelengths.

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