IMPROVED MILLIMETER-WAVE MIXER PERFORMANCE ANALYSIS USING A DRIFT DIFFUSION CAPACITANCE MODEL

Imran Mehdi*, Peter H. Siegel*, and Jack East+

*Jet Propulsion Lab., California Institute of Technology, Pasadena, CA 91109
+Center for Space Terahertz Technology, University of Michigan, Ann Arbor, MI 48109

ABSTRACT

The capacitance-voltage characteristic of a Schottky diode as derived from Poisson's equation predicts erroneously high values of capacitance for large forward bias. The use of this capacitance model predicts temperature dependent mixer noise performance in contradiction with experimentally measured trends. It is shown that by using a drift-diffusion model for the diode capacitance the computed mixer performance is in better agreement with experiments. The need for better diode models to accurately predict high frequency temperature dependent mixer noise performance is also emphasized.

INTRODUCTION

It has been known for some time (1) that lowering the ambient 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 300K to 20K (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 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 results as a function of temperature (4). In an attempt to alleviate this discrepancy an improved model to calculate the capacitance-voltage(C-V) relationship of the diode at high forward bias was developed. Using the improved model we are able to predict the mixer performance in better accord with experiments. The analysis and results presented in this paper emphasize the importance of correctly modeling the diode when analyzing mixer performance at either high frequencies or low ambient temperatures.

SCHOTTKY DIODE 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 depend on an accurate equivalent circuit for the nonlinear element and, in the case of Schottky diode mixers, on knowing the large signal current and capacitance over the full range of instanteous junction voltages(a function of pump power and bias setting). The commonly used analytic expression for the voltage dependent capacitance can be derived by calculating the depletion region width (via Poisson's equation) and defining the per unit area capacitance of the device as $C = \epsilon/d$ where d is the depletion region width and ϵ is the dielectric constant. The analytic expression can be written as [see for example 6]

$$C(V) = \frac{C_{j0}}{(1 - V/\phi_b)^{0.5}} \qquad (1)$$

where C_{j0} is the zero bias capacitance, V is the applied voltage, ϕ_b is the barrier height and the exponent in the denominator is a function of the doping profile. The above expression is based on the assumptions that the electron concentration in the depletion region is negligible and that there is an abrupt depletion layer edge. It is clearly not valid at and above the flatband voltage where it has a sigularity. In room temperature mixers the flatband voltage is generally exceeded only under nonoptimal mixer operating conditions, however at cryogenic temperatures the flatband voltage is easily exceeded when operating at the predicted noise minimum (4). In order to correctly predict the device capacitance under large forward bias conditions a better model is needed.

A range of Schottky barrier device models are available. The two extremes for analytic models are the thermionic emission model and the diffusion theory. A complete review of the possible models and approximations is given in Chapter 5 of reference 6. These models both predict an exponential current vs. applied voltage characteristic, although the internal assumptions and saturation currents are different. The thermionic emission model is useful when de-

AA

scribing current flow over a barrier and the diffusion theory is more accurate in a device simulation where charge redistribution effects and conditions beyond the flatband voltage are present. In our numerical model, Poisson's equation and the current continuity equation are solved self consistently to find the total current (the sum of the electron current and the displacement current) as a function of time through the device. The field dependent mobility is determined by

$$\mu_n = \frac{v_{sat}}{E_o + E} \qquad (2)$$

where v_{sat} is the electron saturation velocity, assumed to be 1×10^7 cm/s, E is the electric field and E_o is the critical field, assumed to be 1×10^3 V/cm. The Einstein relation is used to relate the mobility to the diffusion coefficient. The diode capacitance is found by stepping through a series of bias points, and running the simulation until a steady state current is obtained, finding the charge in the device, and then calculating the derivative of the charge with respect to the voltage. The code can be used over the full range of possible diode junction voltages from reverse bias to beyond flatband. Similar techniques have been reported elsewhere (7,8).

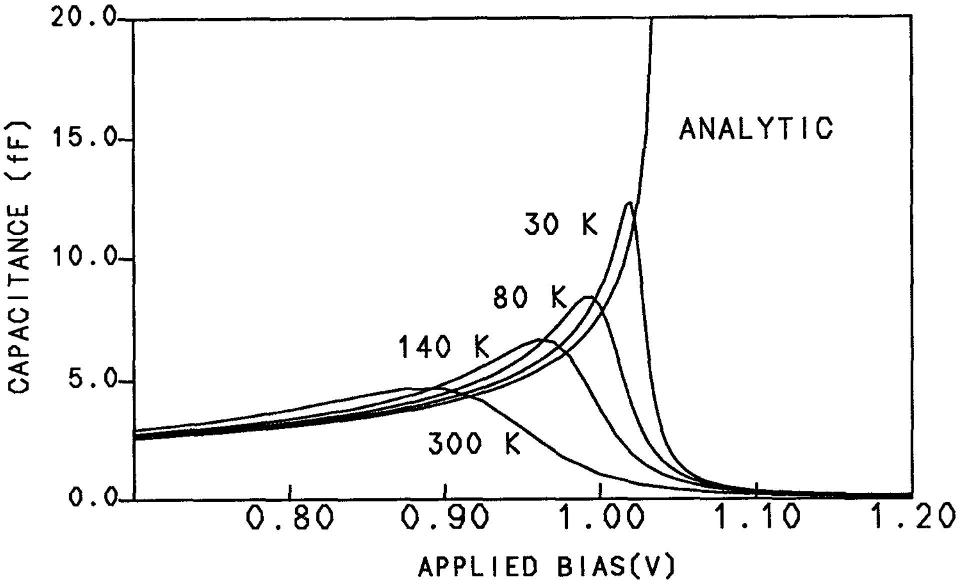

Figure 1: Numerically calculated C(V) characteristics for a Schottky diode at various ambient temperatures. The analytical C(V) is shown for comparison.

Typical C-V curves as a function of diode physical temperature calculated using our numeric model are compared to the analytic expression (eq. 1) in Fig. 1 using data from a realistic submillimeter-wave GaAs Schottky barrier diode (9). The drift-diffusion capacitance at zero bias has been multiplied by a constant so that the computed zero bias capacitance equals the measured zero bias capacitance of the diode under consideration. The trends predicted by the numeric calculations show some interesting behavior. For all temperatures the drift-diffusion C(V) agrees quite well with the analytic C(V) for small and moderate bias levels. Close to flatband conditions the drift-diffusion capacitance differs greatly from the analytical capacitance. This can be attributed to the fact that in the drift-diffusion model the depletion region width is smeared over several Debye lengths due to the nonneglibible electron concentration in the depletion region. The spread in the depletion layer edge produces an averaging effect on the width of the depletion layer and a reduction in the capacitance for bias voltages near the barrier voltage. Decreasing the temperature decreases the Debye length and reduces the charge in the depletion layer. This reduces the averaging effect and causes the capacitance to increase. Thus the peak capacitance of the device increases with decreasing temperature. This model still assumes a quasi-static capacitance and does not take into account hot electron effects which might be important at high applied bias (11).

MIXER RESULTS AND DISCUSSION

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 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 source impedance, bias and local oscillator power level have been varied to achieve lowest noise. The results of the fundamental mixer analysis are plotted in Fig. 2 along with those of an identical study using the analytic expression for the capacitance but with a limit of $50C_{j0}$ below flatband and an abrupt change to $C_{j0}/1000$ above flatband. Table I gives additional numeric results.

Fig. 2 clearly shows the erroneous trend predicted by the analytic expression for the capacitance as the temperature drops below 100K. 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. The drift-diffusion model predicts a continual decrease in total noise with ambient temperature. The trend is corroborated by measurement results on similar diodes (10) although the predicted noise temperature and conversion loss are substantially lower than that actually obtained at these frequencies. This may be due in part to the omission of hot electron noise, intervalley scattering, diode heating and high frequency transport effects in the analysis (11).

Diode and Mixer property	300 K	140 K	80 K	30 K
Saturation Current, (A)	1.0×10^{-17}	1.7×10^{-32}	1.4×10^{-43}	5.6×10^{-50}
Series resistance, (Ω)	24	31	37	37
C_{j0}, (fF)	1.5	1.5	1.5	1.5
Ideality factor	1.11	1.28	1.66	3.86
Barrier height, (eV)	1.04	1.07	1.07	1.07
T_M(SSB), (K)	662	564	417	340
Conversion loss, (dB)	6	6	6	7
P_{LO}, (mW)	1.6	2.2	2.3	2.4
Z_{in}, (Ω)	89+j62	90+j63	94+j66	89+j59
Z_{out}, (Ω)	205-j6	210-j7	222-j8	181-j5
V_{dc},(V)	0.70	0.80	0.85	0.90
I_{dc},(mA)	2.5	3.0	3.0	3.0

Table 1: 600 GHz mixer performance at various temperatures. Mixer IF is 10 GHz and the analysis assumes an ideal 3 port mixer with equal terminations at signal, image and LO frequencies and short circuits at the higher harmonics.

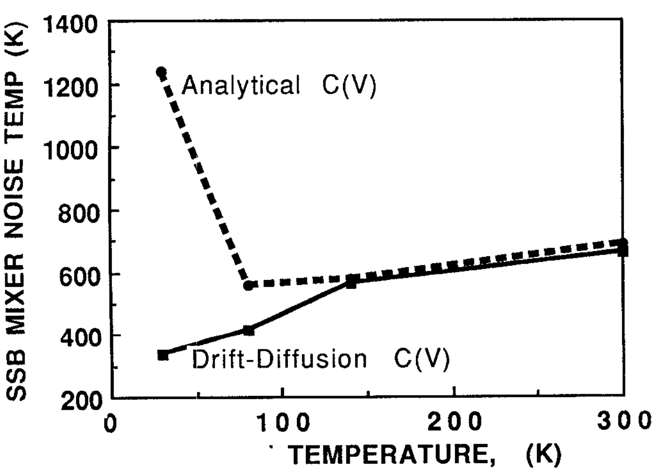

Figure 2: Mixer noise temperature as a function of diode physical temperature calculated with the analytically and numerically determined capacitance- voltage characteristics.

Some of the analysis results are surprising and deserve further investigation. First, the predicted improvement in noise performance at and below 80K is not as great as one obtains experimentally at these frequencies (10). Second, the analysis predicts that both the optimal bias current and the required LO power level do not decrease with physical temperature. One would expect that as the physical temperature is reduced and the diode I(V) curve becomes sharper, the required optimum LO power and rectified current should decrease. In fact, this is generally observed in the laboratory. The absence of this trend leads one to speculate that perhaps the diode parasitics are being overestimated in our model. In order to gain an estimate of the magnitude of the effect the computer simulation was run on a device whose series resistance was kept constant at 10 Ohms instead of increasing with decreasing temperature. The required LO power for optimum mixer noise temperature is plotted in Fig. 3 as a function of diode physical temperature. Three cases are shown. The top curve refers to the situation where room temperature series resistance of 24 Ohms is assumed and the series resistance increases with decreasing temperature as shown in Table 1. The middle curve shows the case where the series resistance is assumed to be a constant 24 Ohms and the bottom curve depicts the LO power requirement when the series resistance is assumed to be a constant 10 Ohms. The computed mixer performance results for the cases where the series resistance is kept constant as a function of temperature are given in Table 2. As suspected, by reducing the series resistance the mixer performance not only improves with decreasing tem-

Mixer property	300 K		30 K	
	$R_s = 24\ \Omega$	$R_s = 10\ \Omega$	$R_s = 24\ \Omega$	$R_s = 10\ \Omega$
T_M(SSB), (K)	662	284	316	89
Conversion loss, (dB)	6	4	6	4
P_{LO}, (mW)	1.6	1.35	1.23	0.65
Z_{in}, (Ω)	89+j62	80+j60	80+j60	60+j60
Z_{out}, (Ω)	205-j6	206-j6	188-j7	215-j10
V_{dc},(V)	0.70	0.6	0.9	0.85
I_{dc},(mA)	2.5	2.5	2.5	1.5

Table 2: Mixer performance for two different values of the diode series resistance at 300 and 30 K. All other parameters are the same as those given in Table 1.

perature but the required LO power and rectified current now also show the expected trends. These results point to a need for further refinement of the diode equivalent circuit, especially in the region of large forward bias.

CONCLUSION

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 and (2) the necessity for using an accurate model for the capacitance variation with voltage in regions of large forward conduction. Improved but not complete agreement between the predicted and measured performance with decreasing temperature emphasizes the need for better diode models in order to predict realistic mixer performance at submillimeter wavelengths.

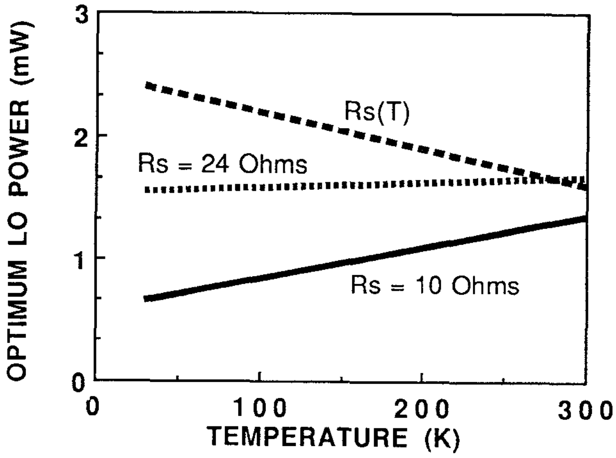

Figure 3: Required LO power for optimum noise temperature as a function of physical temperature for various values of the diode series resistance.

ACKNOWLEDGEMENTS

The authors would like to thank Dr. Tom Crowe (University of Virginia) and Dr. Neal Erickson (University of Massachusetts) for supplying performance data used in the paper and Dr. Erik Kollberg(Chalmers University, Sweden) for supplying a helpful reference. The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration and was sponsored by the Eos program office. One of the authors (IM) was supported by a National Research Council Associateship.

REFERENCES

(1). S. Weinreb and A.R. Kerr,"Cryogenic cooling of mixers for millimeter and centimeter wavelengths," IEEE J. of Solid-State Circuits, SC-8, Feb. 1973, pp.58-63.

(2). A.R. Kerr,"Low-noise room-temperature and cryogenic mixers for 80-120 GHz," IEEE Trans. MTT, MTT-23, Oct. 1975, pp. 781-787.

(3). N.J. Keen,"Low-noise millimetre-wave mixer diodes:result and evaluation of a test programme," IEE Proceedings, vol. 127, pt. 1, Aug. 1980, pp. 188-193.

(4). P.H. Siegel,"Predicted 600 GHz radiometer performance as a function of ambient temperature," Eos-MLS Receiver Development Group Technical Memoranda Series, No. 1, November 29, 1989, 8 pages.

(5). P.H. Siegel, A.R. Kerr and W. Hwang,"Topics in the optimization of millimeter-wave mixers," NASA Tech. Paper 2287, March 1984, 512 pages.

(6). S.M. Sze, Physics of Semiconductor Devices, Wiley, 1969, pp.371-2.

(7). J. J. Liou and F. A. Lindholm,"Capacitance of semiconductor p-n junction space-charge layers: An overview," Proceedings of the IEEE, v. 76, no. 11, November 1988, pp. 1406-22.

(8). H. Hjelmgren, E. Kollberg and L. Lundgren,"Numerical simulation of capacitance of forward-biased Schottky diodes," submitted to IEEE Trans. Electron Devices, Sept. 1990.

(9). 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.

(10). N.R. Erickson, private communication.

(11) T.W. Crowe and R.J. Mattauch,"Analysis and optimization of millimeter- and submillimeter-wavelength mixer diodes," IEEE Trans. MTT, vol. MTT-35, no. 2, Feb. 1987, pp.159-68.