Temperature Variable Noise and Electrical Characteristics of Au–GaAs Schottky Barrier Millimeter-Wave Mixer Diodes

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Abstract —Gold–gallium arsenide Schottky barrier diodes on MBE-grown epitaxial gallium arsenide intended for cryogenic mm-wave mixer applications have been fabricated and characterized. The Schottky barriers were formed either by pulse plating or by *in situ* evaporation in the MBE system after the epitaxial growth. The equivalent temperature Θ as derived from the current–voltage characteristic (equal to the ideality factor η times the physical temperature T_0), important for low noise, is considerably lower at high current densities and cryogenic temperature as compared with the more commonly used Pt–GaAs Schottky diode. Noise generation mechanisms are investigated as a function of forward bias and temperature. At cryogenic temperature we obtained at best an equivalent noise temperature of 22 K at 4 GHz for dc-biased diode, which to our knowledge is the lowest reported for GaAs diodes. Results from mixer measurements at millimeter wavelengths and cryogenic temperature are presented and discussed.

I. Introduction

THE MOST RELIABLE and cost-effective low-noise receivers above 60 GHz are today based on cryogenically cooled small-area Schottky barrier diode mixers. It has previously been shown that the noise properties of such a mixer are critically dependent on the properties of the Schottky diode and especially on the quality of the metal–semiconductor interface [1]–[8]. Currently, most mm-wave mixer diode manufacturers use platinum as the Schottky metal in spite of its tendency to react with GaAs [7], [8], forming different compounds at the metal–semiconductor interface that may degrade the mixer performance.

In this work, we have investigated Au–GaAs Schottky diodes, since gold is known to be less reactive on GaAs than platinum. Consequently more ideal electric characteristics can be expected. Since the performance of the diodes is critically dependent on the fabrication, some important fabrication steps are described and discussed.

It can be shown that mixer properties, and in particular the mixer noise, are closely related to features found in the $I-V$ characteristic and noise performance of the dc-biased diode. Consequently these diode characteristics are investigated in detail. The results are compared with previous results obtained from measurements on Pt–GaAs Schottky diodes.

Finally, measurements of mixer properties of Au–GaAs diodes are presented and discussed.

II. Fabrication Procedures

Two sets of diodes with gold anodes, CTH 2545 and CTH 928, were fabricated using somewhat different procedures. Both diodes are of the Mott type; i.e., the epi layer is depleted except for very high forward voltages. CTH 2545 has a lowly doped epi layer to decrease the shot noise. The Schottky metal on CTH 928 is deposited inside the MBE growth chamber in order to achieve a clean interface between metal and semiconductor.

The substrates are horizontal Bridgeman Si-doped ($N_d = 2\text{–}3 \cdot 10^{18}$ cm^{-3}) GaAs. The epi layer on CTH 928 was grown in a Varian 360 MBE system at Chalmers University of Technology. The growth rate was 1 μm/h and the substrate temperature was 600°C. The material parameters of the diodes are listed in Table I.

The CTH 2545 material was processed in the following way. After MBE growth, 0.45 μm of SiO_2 was deposited by atmospheric pressure CVD (chemical vapor deposition), the wafers were thinned down to 125 μm, and AuGe ohmic contacts were formed on the backsides. After photolithography, holes were etched in the SiO_2 using a CF_4 plasma. The holes were then etched by dilute buffered HF, although there was no visual oxide left after the plasma etching. In order to eliminate surface damage, caused by the different coefficients of thermal expansion for SiO_2 and GaAs [6], 100–150 Å of GaAs was etched away by $NH_4OH/H_2O_2/H_2O$ (10/0.1/150) before immersion in

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TABLE I
DIODE MATERIAL PARAMETERS

Diode	Schottky metal deposition	Epi thickness (Å)	Nominal doping concentration (cm^{-3})	Diode area (μm^2)	Series resistance (Ω)
CTH 2545[2]	pulse plating	2000	$5 \cdot 10^{15}$	7	5
CTH 928[1]	MBE *in situ* evaporation	1500	$2 \cdot 10^{16}$	5–7	7–13[3]

[1]The MBE material was grown at the Physics Department, Chalmers University of Technology, Göteborg, Sweden.
[2]The MBE material was grown at Max Planck Institut für Festkörperforschung, Stuttgart, Germany, by Klaus Ploog.
[3]The $\log(I)-V$ characteristic has no linear part at 20 K, so it is impossible to evaluate a constant R_s for any voltage range at this temperature.

NH_4OH/H_2O (1/15) for 30–45 s. Immediately following the ammonia dip, which removes the oxides Ga_2O_3 and As_2O_3, 0.2 μm of Au was pulse electroplated into the holes etched in the SiO_2.

The CTH 928 diodes are less conventional, since the Schottky contact is formed in the ultrahigh vacuum of the MBE system. While still in the MBE chamber the temperature of the substrate was reduced to 85°C. On a surface showing a sharp RHEED pattern with a C(2*8) As stabilized reconstruction, a 2500 Å thick layer of gold was deposited. The RHEED pattern remained fairly sharp during the deposition, but the epitaxial relationship could not be unambiguously determined. The background pressure, formed mainly by As_4, was $3 \cdot 10^{-8}$ torr during the evaporation. Standard photolithographic procedures were used to form resist islands with diameters of 3 μm. The resist was postbaked to give a rounded edge profile. Mesa diodes were formed by ion beam milling in an argon atmosphere down to at least 500 Å into the buffer layer. The resist was then exposed to an O_2 plasma in a planar plasma etch reactor to cause the resist edge to recede about 0.1–0.2 μm. The Ga and As oxides thus formed were not removed before a 0.2 μm thick layer of SiO_x was evaporated over the entire surface. Liftoff was carried out using acetone and ultrasonic agitation. The wafer was thinned and cleaned before Ni–AuGe was evaporated on the backside of the wafer. Since the Au–GaAs Schottky contact is sensitive to high temperatures, ordinary furnace alloying was judged unsuitable. An attempt to rely solely on laser alloying had to be abandoned, however, as the high reflectivity of the metal entailed more laser power than available from our argon laser. By careful heat treatment in a furnace, 300°C/30 min, the series resistance resulting from the laser alloying, i.e., 90–100 Ω, was reduced by an order of magnitude without affecting the $I-V$ characteristic of the gold Schottky contact significantly (Fig. 1).

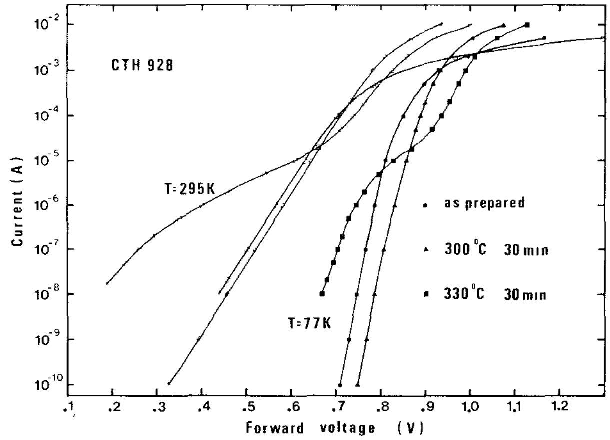

Fig. 1. The $I-V$ characteristic of the gold-mesa diode CTH 928 for different annealing conditions.

III. INVESTIGATION OF DIODE PROPERTIES

Of particular importance for judging the expected performance of a Schottky diode in a mixer are measurements of the dc $I-V$ characteristic and the noise generated by the diode when dc-biased, together with proper interpretation. The $I-V$ characteristic can be separated into two major regimes, the low-current regime and the high-current regime. The former yields the diode effective temperature and ideality factor. In the high-current regime space-charge phenomena and hot electron effects in the epi layer become important. The noise temperature clearly shows evidence of hot electrons in the epi layer.

A. The Diode Effective Temperature and Ideality Factor

The temperature variable current–voltage characteristics for all diodes were measured, using a pA meter, in the range 10 pA–10 mA. Fig. 2 shows the $\log(I)-V$ characteristic for diode CTH 2545 at temperatures from 20 K to 295 K. The measured characteristic is approximated by

$$I = SA^*\Theta^2 \exp\left[\frac{q(V-\phi_b-IR_s)}{k\Theta}\right] \quad (1)$$

where V is the applied voltage, ϕ_b is the barrier height, and I, S, and A^* are, respectively, the diode current, the diode area, and the modified Richardson constant ($8.2 \cdot 10^4$ $Am^{-2}K^{-2}$). Θ is the effective temperature, which differs from the physical temperature T_0 of the device because of a number of phenomena such as barrier height lowering mechanisms and tunneling [9]. The well-known "ideality factor" can be expressed as $\eta = \Theta/T_0$. The series resistance R_s can be determined from the $I-V$ characteristic [10]. Θ

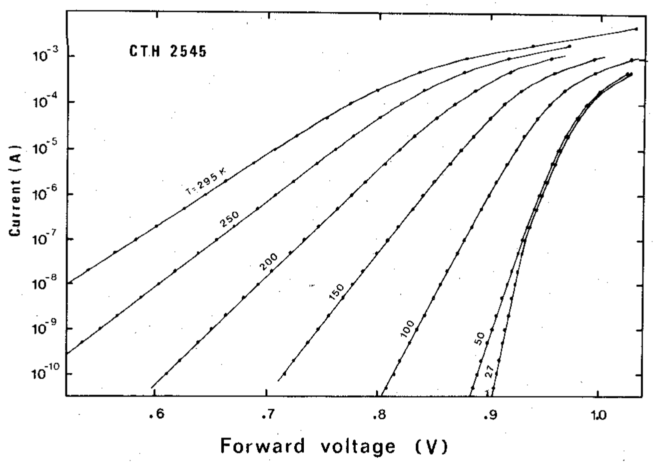

Fig. 2. The temperature-dependent $I-V$ characteristic for the pulse-plated gold diode CTH 2545.

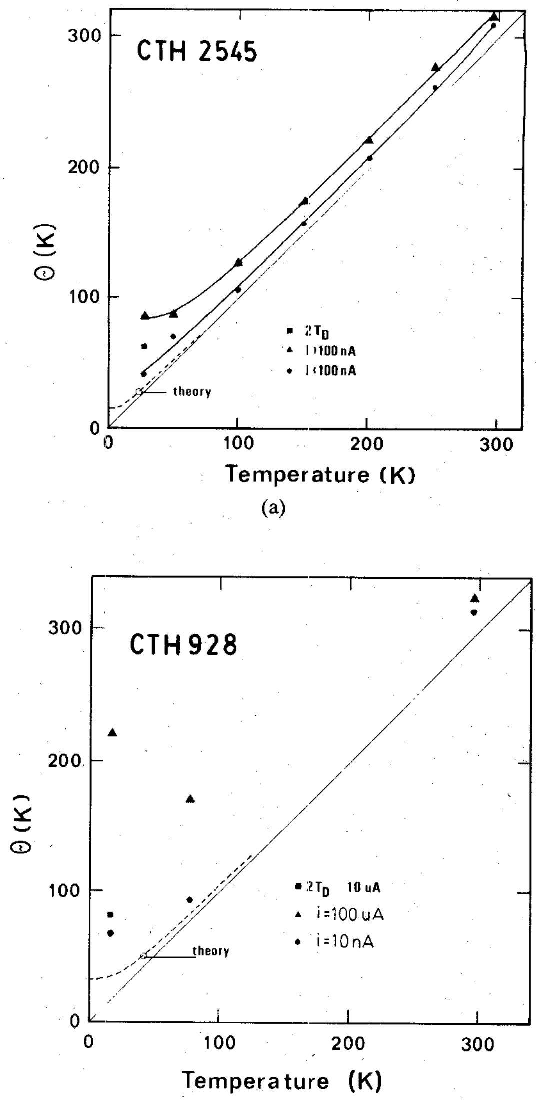

Fig. 3. The "effective temperature," Θ, versus physical temperature for the diodes.

is also determined from the $I-V$ characteristic since

$$\Theta = \frac{qI}{k}\left(\frac{dV}{dI} - R_s\right). \tag{2}$$

Θ is plotted in Fig. 3 for the different diodes. Since Θ at low temperatures usually changes abruptly from one value to another, at some breakpoint current(s), two or more values of Θ have to be specified in order to accurately describe the slope of the $I-V$ characteristic (see Figs. 1 and 2). In Fig. 3, the theoretical Θ_{P-S} given by Padovani and Stratton [11] is plotted:

$$\Theta_{P-S} = \Theta_0 \coth(\Theta_0/T) \tag{3}$$

where Θ_0 is the zero temperature limit:

$$\Theta_0 = \frac{qh}{2\pi k}\sqrt{\frac{N_d}{4\epsilon m^*}}. \tag{4}$$

N_d, ϵ, and m^* are the doping concentration, the dielectric permittivity of GaAs, and the effective mass of electrons in GaAs, respectively, while the other symbols denote the usual constants. From Fig. 3 it is clear that the measured Θ agrees fairly well with this theory only at very low currents.

B. The Low-Current Regime

As for Pt–GaAs diodes [3], often more than one slope parameter can be distinguished in the $\log(I)-V$ characteristic. Two mechanisms have been proposed to explain the higher values of Θ at higher currents: a lateral variation of the barrier height at the Schottky contact [3], [4], and a field-dependent barrier height [3]. In the first case one expects the noise temperature to be slightly higher than the lowest measured value of Θ divided by two, the theoretical shot noise [12], [13], while the field-dependent barrier height should cause a noise proportional to the inverse of the derivative of the $\log(I)-V$ curve. Since experimental evidence rather supports the first model (the inhomogeneous Schottky contact), the relevance of evaluating Θ for higher currents and associating these numbers with shot noise is doubtful, and will not be pursued below.

However, a lower value of Θ for high currents can be interpreted as a measure of higher diode quality; i.e., the barrier height is more uniform over the diode surface. Hence, the Θ value for higher currents is an important parameter for judging the quality of a diode. Of particular interest should be the slope parameter in the current regime 1 μA–1 mA, which we estimate to be the important current regime where noise from the diode is coupled to the intermediate frequency in a practical mixer. As seen from Fig. 3(a) and (b), twice the measured noise temperature at 4 GHz and 10 μA typically equals 1.3 times the Θ value measured at low currents. Comparing Θ values of Au–GaAs diodes in the current regime 1 μA–1 mA with the results obtained for Pt–GaAs diodes, Au–GaAs diodes in general more consistently show low Θ values. The Au–GaAs diodes typically have Θ values of the order of 100 K or lower at an ambient temperature of 20 K (except diode CTH 928, which has a higher Θ due to a not fully optimized fabrication procedure), while for Pt–GaAs diodes we have typically obtained 150–400 K.

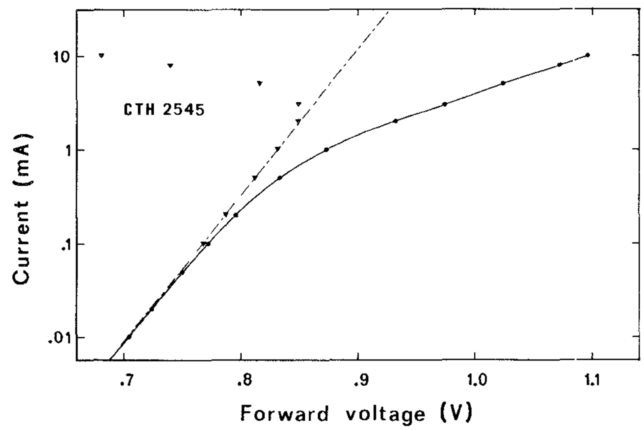

Fig. 4. The high current $I-V$ characteristic for diode CTH 2545 showing a nonlinear series resistance.

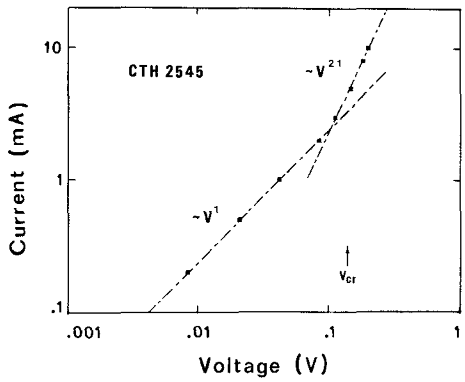

Fig. 5. The $I-V$ characteristic of the series resistance for CTH 2545.

C. The High-Current Regime

It was previously shown on Pt–GaAs diodes [14], [15] that in the high bias current regime, where the voltage drop across the series resistance is significant, the current–voltage characteristic of the barrier only (i.e., the $I-V$ characteristic when the voltage drop over the series resistance is subtracted) remains exponential up to a certain limiting current. Above this current, depending on the diode parameters, the series resistance will either decrease (due to space charge injection of electrons from the N+ substrate [16]) or increase (due to intervalley scattering). This behavior should be independent of the type of Schottky metal used and consequently it should be present also on the diodes used in this work.

Fig. 4 shows the high-current regime of diode CTH 2545. This diode has a low epi layer doping concentration ($5 \cdot 10^{15}$ cm^{-3}), which facilitates the observation of the phenomena to be discussed. The dots in Fig. 6 correspond to the measured values, and the triangles correspond to the "intrinsic" (barrier) $I-V$ characteristic, assuming a constant series resistance. Note that the intrinsic $I-V$ is exponential in the "constant series resistance region" over about one decade of current. Obviously, the series resistance seems to decrease with increasing current above 2 mA. Space-charge injection from the N+ contact layer can explain this behavior. According to Gregory and Jordan [17], the crossover voltage

$$V_{cr} = N_D q L^2 / 2\epsilon \qquad (5)$$

where L is the thickness of the low doped GaAs layer, gives the breakpoint between the ohmic region and the Child's law region (where $J \sim V^2$). We obtain the series resistance voltage drop approximately as the difference between the measured voltage and the intrinsic extrapolated diode voltage. The result is shown in Fig. 5. In the nonohmic region, the current is proportional to V^K, where K is a constant equal to 2.1 at 295 K and 1.7 at 20 K for CTH 2545. (In the ohmic region K is, of course, one.) V_{cr} is marked in the figure and corresponds fairly well to the experimental breakpoint. Similar nonohmic behavior can be seen also on diodes with more heavily doped epi layers (in the 10^{16} cm^{-3} range). The breakpoint between the ohmic and nonohmic behavior of the series resistance then occurs at current levels where velocity saturation effects are expected [15], [18].

D. Noise Characteristics

The noise properties versus forward current of the diodes were characterized at 4 GHz (3.7–4.3 GHz), at ambient temperatures of 20 K and 295 K, using a previously described measurement technique [14]. In brief, the noise from the diode is first amplified by a low-noise circulator-coupled FET amplifier; it is then mixed down to 30 MHz, amplified, and detected by a square law detector and presented on a scalar network analyzer. By comparing the noise power from the diode with the noise power from a resistive load and measuring coupling loss (power reflection), the noise temperature (T_d) of the diode can be deduced. Fig. 6 shows the measured noise temperature, T_d, for the diodes versus forward current. The electric field in the epi layer was estimated as $I \cdot (R_s - R_{sub})/L_{epi}$, where R_s is the measured series resistance, R_{sub} is the calculated spreading resistance of the substrate, and L_{epi} is the thickness of the epi layer.

The result of the noise characterization is in many respects consistent with our measurements on Pt–GaAs diodes [14], [15]. At room temperature and if the electric field in the epi layer is below approximately 1 kV/cm, the noise is determined by shot noise from the junction and Johnson noise from the series resistance. Above 1 kV/cm, the electrons are heated by the electric field, causing an increase of the diode noise temperature. The noise temperature of Pt–GaAs diodes at high frequencies was found to be well described by [15]

$$T_d = \frac{r_b T_{sh} / \left(1 + (\omega r_b C_b)^2\right) + R_{epi} T_{epi} + R_{sub} T_{sub}}{r_b / \left(1 + (\omega r_b C_b)^2\right) + R_{epi} + R_{sub}}. \qquad (6)$$

Here r_b, C_b, ω, R_{epi}, R_{sub}, T_{sh}, T_{epi}, and T_{sub} are, respectively, the barrier differential resistance, the barrier capacitance, the angular frequency, the epi layer contribution to the series resistance, the resistance of the substrate and the

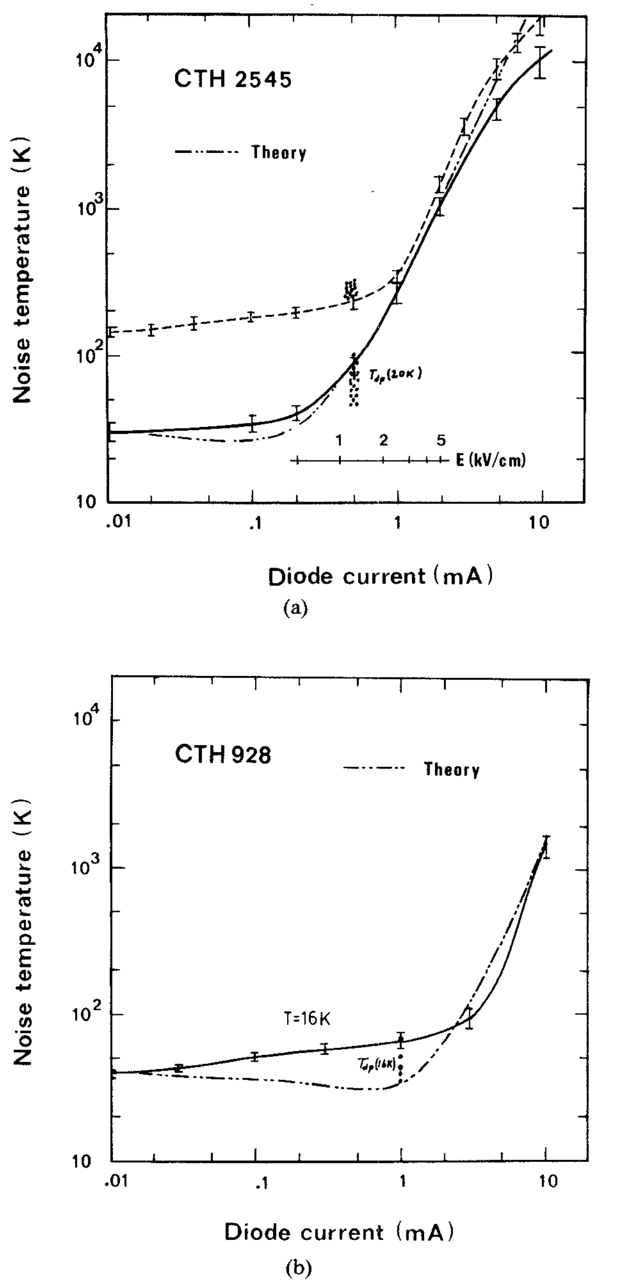

Fig. 6. The current dependent noise temperature, T_d, for the diodes at $T = 20$ K and 295 K. The measurement frequency is 4 GHz. The dots correspond to T_{dp}, obtained from mixer measurements.

back contact, the shot noise temperature, the epi layer noise temperature, and the noise temperature of the substrate and back contact.

The hot-electron contribution to the epi layer noise temperature was estimated by using the energy and momentum balance equations [18], [19], which yield

$$T_{\text{epi}} = T_0 + \frac{2q^2\tau_m\tau_e E^2}{3km^*}. \tag{7}$$

T_0, τ_m, τ_e, and E are the ambient (lattice) temperature, the momentum and energy relaxation times, and the electric field. At low fields $T_{\text{epi}} = T_0$, which is the Johnson noise limit.

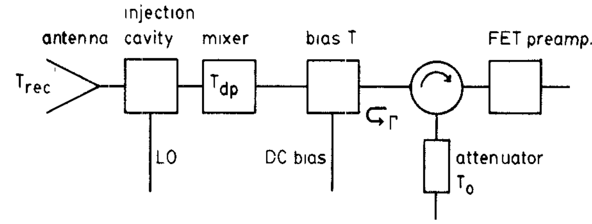

Fig. 7. The mixer measurement setup.

The noise behavior of the Au–GaAs diodes is also generally in agreement with this model, and the noise temperature starts to increase at a field of the order of 1 kV/cm at $T_0 = 295$ K and 0.5 kV/cm at $T_0 = 20$ K due to heating of the electrons. For both diodes the noise temperature is in agreement with (7) and $T_d \sim I^2$ at high fields, as expected. A decreasing slope of the noise temperature–current characteristic (at $T_d > 4000$ K) for diode CTH 2545 can, however, be seen at currents above approximately 2 mA, which may be an effect of the carrier injection as discussed previously (Fig. 5). This behavior was also observed on some Pt–GaAs diodes. The shot noise component, T_{sh}, at low currents (10 μA) is 150 K at $T_0 = 295$ K, in good agreement with (6), and 30 K at $T_0 = 20$ K. The lowest noise temperature, 22 K at 10 μA, was measured on a similar diode where the epi layer had been chemically etched down from 2000 Å to nominally 1400 Å. This is to our knowledge the lowest reported noise temperature for a Schottky diode.

For the diode CTH 928, in the current range 20 μA–2 mA, the noise increases slowly with current, which is not expected from the above analysis. The noise at low currents, 10 μA, is 40 K.

E. Mixer Measurements

Measurements on cryogenically cooled diode mixers were made in our *R*-band (75–110 GHz) mixer block, described elsewhere [20], and the measurement setup shown in Fig. 7 was used. The mixer is designed for the intermediate frequency (IF) band 3.7–4.3 GHz. Best mixer results were obtained with diode CTH 928. At a LO frequency of 100 GHz, the best single sideband receiver temperatures are 204 K at the lower sideband and 201 K at the upper sideband, with associated conversion losses of 6.5 dB and 5.8 dB, respectively. Of particular interest is also the mixer noise temperature:

$$T_M = T_{\text{rec}} - T_{\text{IF}} \cdot L_{\text{tot}} \tag{8}$$

where L_{tot} is the conversion loss from the signal input port, including the horn antenna, to the input port of the IF amplifier. T_M is 118 K and 134 K at the upper and the lower sideband, respectively. The noise temperature of the IF amplifier is 18 K. The image is short-circuited by a movable backshort. The conversion loss at the image frequency is at least 20 dB larger than at the signal frequency. The single sideband operation simplifies the evaluation of the diode noise temperature, T_{dp}, considerably. According to the attenuator noise model for resistive diode mixers [21], the input noise temperature for a single sideband mixer (excluding the contribution from the IF amplifier) is

$$T_M = T_{dp}(L-1) \tag{9}$$

where T_{dp} is the equivalent temperature of the pumped diode, dependent in general on the noise generated by the diode, the nonlinear capacitance, the series resistance, and the embedding network. L is the conversion loss excluding reflection loss at the IF output.

Since a complete mixer analysis, including both the solution of the (nonlinear) problem of finding the current and voltage waveforms of the diode, and a small-signal analysis including all important noise sources [22], [23] is quite complicated, (8) and (9) are often used to characterize a mixer diode. This was done in this work and the results are marked with dots in Fig. 6(a) and (b) for different SSB backshort positions and at a current equal to the rectified current of the mixer at optimum performance. The agreement between T_{dp} and the noise from the dc-biased diode, T_d, at the same current is fair.

IV. Discussion

In order to develop better mixer diodes for cryogenic operation, it is important for the magnitude of the shot noise to be as low as possible, and the mixer operating current to be well below the current where hot-electron noise starts to dominate. Our measurements indicate that it is possible to fabricate diodes which have a steeper current–voltage characteristic and lower shot noise by using gold instead of platinum as the Schottky metal. Diode CTH 928, having more conventional material parameters, yields mixer results comparable to the best Pt–GaAs diodes tested in our lab in the same mixer structure. It is expected that the MBE-deposited anode mesa diodes could be further improved if the ohmic contact is formed in a different way, for instance by spark alloying [24], since the high-temperature anneal used at present probably causes some Ga outdiffusion into the Au layer [8] and thus some degradation of the metal–semiconductor junction. The slow increase in the noise versus current characteristic shown in Fig. 6(b), below 2 mA, could then hopefully be avoided, which would yield still better noise and mixer performance.

At low currents and low temperature, where the differential resistance is much larger than the series resistance, the dominant noise source should be shot noise. When comparing $\Theta/2$, where Θ is obtained from the $I-V$ characteristic, with measured noise at the same bias, the measured noise is lower. See also Fig. 3, in which $2T_d$ is marked. However, the measured noise is slightly larger than $\Theta/2$ if Θ is determined from the steepest part of the $I-V$ characteristic (nA region). This result was also found on Pt–GaAs diodes [3]. This may be explained by the model of parallel diodes, related to barrier height variations over the diode surface [3], [4], which cause the current density to vary laterally within the diode. This phenomenon might also result in larger conversion losses as well as local electron heating.

Even if Au–GaAs diodes yield promising results, other metal–semiconductor combinations may also be of interest, especially from the point of view of reliability and long-term stability. MBE grown Al–GaAs millimeter-wave mixer diodes have already been fabricated [25] and an improved MBE growth method has given diodes with almost ideal Al–GaAs barriers with an ideality factor of less than 1.02 at room temperature [26].

V. Conclusions

Au–GaAs Mott diodes intended for cryogenic mixer applications were fabricated and evaluated. The motivation for this work was to investigate the impact of the choice of Schottky metal on mixer performance. Current–voltage, dc noise, and mixer properties were measured at different temperatures. An improved ideality factor and low dc-biased noise were noticed. Although not fully optimized yet, diodes based on Au–GaAs metal–semiconductor junctions have shown promising mixer results.

Acknowledgment

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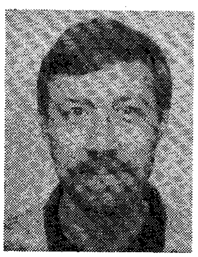

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