PHYSICAL PROPERTIES OF THE POTENTIAL BARRIER OF Pt/n-GaAs SCHOTTKY MIXER DIODES

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Abstract

The temperature dependence of the current-voltage characteristic of Pt/n-GaAs Schottky diodes which are used as mixers in low noise THz heterodyne receivers is investigated. Two different groups of diodes are identified. While the barrier height and temperature dependence of the diodes of one group are determined by the energy gaps of GaAs they are determined by defects at the metal-semiconductor interface for the diodes of the other group. For a defect free interface the barrier height has no influence on the noise performance of the diode. The influence of spatial inhomogeneities at the interface on the noise temperature is investigated. It was found that the noise temperature increases with increasing magnitude of the spatial inhomogeneities.

1. Introduction

It is well known that the electronic properties of Schottky diodes for example their current-voltage (I-V) characteristic and their noise performance depend critically on the microphysical structure of the metal-semiconductor contact [1,2]. Interface defects can pin the Fermi-level and consequently change the barrier height of the diode compared to a defect free interface [3]. Spatial inhomogeneities at the potential barrier can lead to a drastic increase of noise when the standard deviation of their magnitude exceeds a critical value of 2kT [4].

In the course of this study we have investigated the influence of defects on the height and temperature dependence of the potential barrier in Pt/n-GaAs Schottky diodes with different doping densities of the epitaxial layer. All diodes are used as mixers in low noise THz heterodyne receivers. For the diode which currently yields the lowest noise temperature in the frequency range from 1 to 5 THz (diode 1T15 from the University of Virginia [5, 6,7]) it was studied if the barrier height has any significant influence on the noise performance of the diode. In addition, for different contacts of this type of diode the magnitude of the spatial inhomogeneities at the metal semiconductor transition was determined and correlated to the measured noise temperature. Evidence is presented that with increasing magnitude of the spatial inhomogeneities the noise performance of the diode degrades.

2. Experimental Setup

The Schottky contact of all diodes is a submicron-size dot of Pt on a GaAs (100) epitaxial layer which has a doping density between $0.5\text{-}10\times10^{17}$ cm^{-3}. The I-V curves were measured at temperatures varying from 300 K to 80 K. Cooling was performed with a closed cycle He refrigerator. The temperature was measured with a Si temperature diode mounted close to the Schottky contact. In order to make sure that the temperature of the Schottky diode under investigation is the same as the temperature measured by the Si diode a delay of 15 minutes between two measurements was kept. This procedure was checked by replacing the Schottky diode with a Si temperature diode and measuring the temperature with both Si diodes. The difference in the measured temperature between the two Si diodes was always less than 0.2 K. The temperature could be held constant within ± 0.1 K by the use of stabilization loop. The loop consisted of the temperature diode, a heating resistance and a temperature controller, which regulates the temperature to a preset value. All measurements were performed in the dark. The voltage was supplied by a Keithley 236 voltage source, which at the same time measured the current.

As an example, the I-V curves of a Schottky diode 1I7 at different temperatures are plotted in Fig 1. As one can see the I-V curves shift to higher bias voltages and are getting steeper with decreasing temperature.

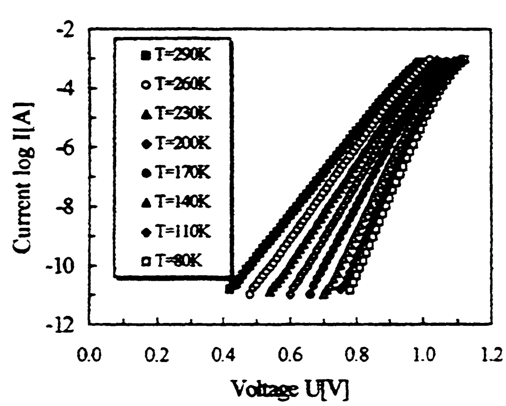

Fig. 1: Current voltage characteristics of the diode 1I7 as a function of temperature.

In order to correlate the microphysical properties of the Schottky contact to the noise performance of the diode when used as a THz mixer in a heterodyne receiver we measured the noise temperature of different diodes at 1.47 THz. A FIR gas laser was used as the local oscillator with $^{13}CH_3OH$ as the lasing medium (CO_2 pump laser line 10R16). The diodes were whisker contacted with a standard 4λ antenna in a corner cube mounting. The noise temperatures were measured by the Y factor method with Eccosorb™ immersed in a liquid nitrogen bath as the cold load and Eccosorb™ at ambient temperature as the hot load. Signal beam and laser beam were superimposed by the use of a Martin-Puplett diplexer. A single stage λ/4 impedance transformer was used. The noise temperatures were measured at an intermediate frequency of 11.1 GHz with a bandwidth of 1 GHz. The first amplifier was cooled to 77K and had a noise temperature of about 100 K. The presented data are double sideband (DSB) noise temperatures and are not corrected for atmospheric losses or losses in the optics.

3. Defects at the Metal-Semiconductor Transition

In the case that the current transport in the Schottky diode is dominated by thermionic emission it can be described by [2]

$$I = I_S \exp(qV/nkT)\,[1-\exp(-qV/kT)]. \quad (1)$$

Here q is the electronic charge, k is Boltzmann's constant, T is the temperature, V the applied forward bias and n the empirical ideality coefficient. I_s is the saturation current given by

$$I_S = A^{**}\, S\, T^2 \exp(-q\,\Phi_{bo}/kT)], \quad (2)$$

where A^{**} is the effective Richardson constant taken as 8.6×10^4 A m^{-2} K^{-2}, S is the anode area and Φ_{bo} is the zero-bias barrier height. n and I_s were deduced from a least squares fit of eq. 1 to the data while Φ_{b0} is determined from I_s with the help of eq. 2. For a given n and Φ_{b0} it is possible to calculate the height of the potential barrier when the semiconductor bands are flat. This is the so called flat-band barrier height. It is worth noting that the flat-band barrier height is independent of the current transport mechanism [8]. Therefore it can also be determined for the highly doped diodes where tunneling contributes significantly to the total current. According to Wagner et al. [8] the flat-band barrier Φ_{bf} is given by

$$\Phi_{bf} = n\Phi_{b0} - (n-1)\,(kT/q)\,\ln(N_C/N_D), \quad (3)$$

where N_C is the effective density of states in the conduction band and N_D is the ionized donor density. Both are functions of the temperature. This is taken into account in our analysis. It has been shown that the flat-band barrier height is the same as the barrier height determined by the capacitance-voltage method [9].

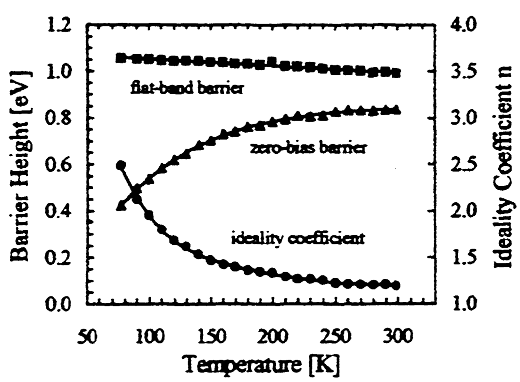

Fig. 2: Ideality coefficient, zero-bias barrier height and flat-band barrier height as a function of temperature for the diode 1I7c.

Fig. 2 shows the ideality coefficient, the zero-bias barrier height and the flat-band barrier height as a function of temperature. While the ideality coefficient decreases with increasing temperature the zero-bias barrier height increases. Especially at temperatures below about 150 K this dependence is quite pronounced. In contrast, the flat-band barrier height decreases weakly with increasing temperature. This decrease can be expressed by

$$\Phi_{bf}(T) = \Phi_{bf}(T{=}0K) + \alpha T. \quad (4)$$

Here Φ_{bf} (T=0K) is the flat-band barrier height extrapolated to 0 K and α is the temperature coefficient. We have analyzed 11 Schottky diodes with different doping densities by this method. The results are given in table 1 (see appendix). For a further analysis the flat-band barrier height is plotted as a function of the temperature coefficient (fig. 3). Obviously there are two groups of contacts. The Schottky diodes of group 1 have a flat-band barrier height of 1.018 ± 0.008 eV. Their temperature coefficient varies between -0.17 meV/K and -0.30 meV/K with a mean value of -0.23 ± 0.02 meV/K. The diodes of the second group have a mean barrier height of 0.922 ± 0.021 eV and a temperature coefficient close to zero (-0.002 ± 0.004 meV/K). It is worth noting that even diodes which are nominally the same can belong to the different groups (e.g. diode 1I7 a-c).

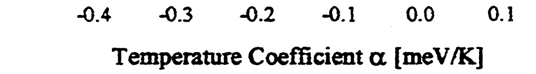

Fig.3: Flat-band barrier height as a function of the temperature coefficient. Two groups of diodes are discernible. It is worth noting that even diodes which are nominally the same can belong to the two different groups (diode 1I7 open symbols).

These findings can be interpreted on the basis of recent models of Fermi-level pinning and barrier formation in Schottky diodes. According to a model developed by Tersoff [10] the barrier height for a metal on n-type GaAs is given by

$$\Phi_{bn} = E_g - ½ (E_g^{\,i} - \Delta/3) - \delta_m\,, \quad (5)$$

where E_g is the direct energy gap (1.42 eV [11]), E_g^i is the minimum indirect energy gap (1.81 eV [11]), Δ is the spin orbit splitting (0.34 eV [11]) and δ_m is an adjustable parameter which takes into account the dependence of the barrier height on the metal. From our measurements of the flat-band barrier height it follows δ_{Pt} = -0.45 eV. This value is reasonable, since the value for gold is -0.33 eV and Pt is more electronegative than Au if one considers the electronegativity values given by Miedema [1].

The temperature dependence of the potential barrier can be easily deduced from eq. 5

$$d\Phi_{bn}/dT = dE_g/dT - ½ dE_g^{\,i}/dT\,. \quad (6)$$

The linearized temperature dependence of the direct energy gap is -0.39 meV/K [11] while for the indirect gap it is -0.43 meV/K [11]. From this a temperature coefficient of -0.18 meV/K is calculated in good agreement with our measurements.

The close to zero temperature coefficients of the Schottky diodes of group 2 are understandable on the basis of a combined model where metal induced gap states as well as defects at the metal semiconductor interface have to be considered. As shown in Ref. [1] defects at the interface result in a decrease of the potential barrier $\delta\Phi_b$ by

$$\delta\Phi_b \approx N_I / D_{MIGS}\,, \quad (8)$$

where N_I is the density of interface states and D_{MIGS} is the density of metal induced gap states ($\approx 3.7\times10^{14}$ eV^{-1}cm^{-2} for GaAs [1]). For the diodes of group 2 $\delta\Phi_b$ is about 0.1 eV which results in a density of interface states of $N_I \approx 3.7\times10^{13}$ cm^{-2}. This is about one fiftieth of the total density of sites of a GaAs (100) plane. In addition, as Revva et al pointed out [12], the temperature coefficient of a potential barrier which is pinned by defects is close to zero. This is due to the fact that the temperature dependence is governed by the ionization entropy of the defects which is almost independent of temperature.

In fig. 4 the DSB receiver noise temperature measured with a diode 1T15 is shown as a function of the flat-band barrier height. It is worth noting that all measurements were made with Schottky contacts from one diode chip in order to have well defined experimental conditions. No dependence of the noise temperature on the flat-band barrier height discernible. However, for all diodes the flat-band barrier height is around 1 eV. In this case the barrier height is not determined by defects. If the influence of defects is negligible the noise temperature of the Schottky diodes does not depend on the barrier height. Since this study does not include contacts were the barrier height is determined by interface defects the question if and how they affect the noise performance is still open.

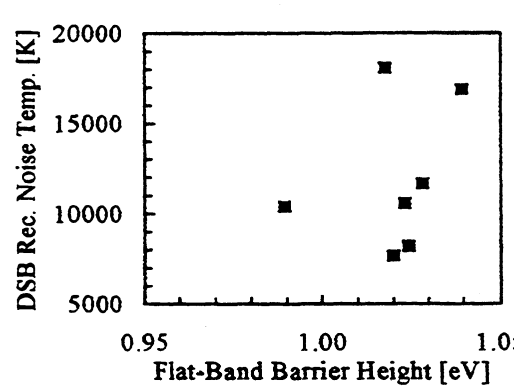

Fig. 4: DSB receiver noise temperature as a function of the flat-band barrier height for the diode 1T15. All contacts are from the same diode chip.

4. Spatial Inhomogeneities at the Metal-Semiconductor Transition

The interface between a metal and a semiconductor is not flat but rough on an atomic scale. These roughness may have different origins. Defects, atomic steps, dislocations, grain boundaries in the metal or irregular distributed donor atoms are a few of them. Spatial inhomogeneities cause a deviation of the measured ideality coefficient of a Schottky diode from the theoretical expected value. In addition, spatial inhomogeneities cause differences between the flat-band barrier height and the zero-bias barrier height of a Schottky diode. It has been shown previously that the noise performance of a Schottky diode depends on the magnitude of the spatial inhomogeneities [4]. In the analysis of our data we follow the approach of Werner and Güttler [3]. They assume that the spatial distribution of the barrier height Φ_b at the metal-semiconductor transition can be modeled by a Gaussian distribution with a standard deviation σ_s around the flat-band barrier height Φ_{bf}

$$P(\phi_b)=(\sigma_s\sqrt{2\pi})^{-1}\exp(-(\Phi_{bf}-\Phi_b)^2/2\sigma_s^2). \quad (8)$$

From this it follows that the difference between the flat-band barrier height and the zero-bias barrier height is given by

$$\Phi_{bf}-\Phi_{b0}=q\sigma_s^2/2kT. \quad (9)$$

Because of the high doping density of the diode 1T15 the lowering of the potential barrier is not only due to inhomogeneities. Tunneling currents and image force cause a barrier lowering with respect to the flat-band. In order to determine the barrier lowering due to inhomogeneities their contributions are subtracted from the flat-band barrier height. Other effects such as generation-recombination currents in the space charge region or defects are negligible for the 1T15 diodes in this study. By taking into account the barrier lowering due to tunneling and image force the standard deviation σ_s of the spatial distribution of the Schottky barrier heights was calculated. Fig. 5 shows the receiver noise temperature as a function of kT/σ_s^2. There is a correlation between both. For all contacts the thermal energy kT of the electrons is smaller than 0.5 σ_s. It is worth noting that in this case where the standard deviation σ_s exceeds a critical value of 2kT a drastic increase of noise was observed for different silicide/Si Schottky diodes [4].

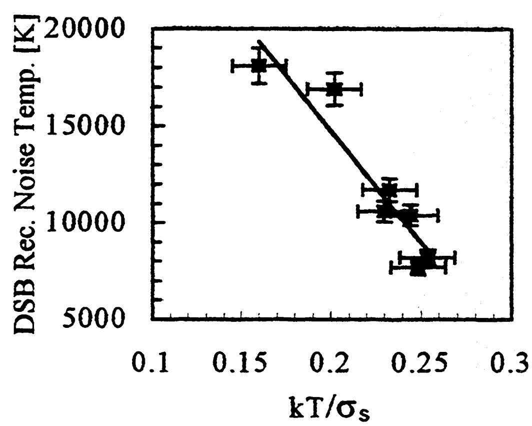

Fig. 5: The DSB receiver noise temperature increases with increasing standard deviation σ_s of the spatial inhomogeneities.

5. Summary

From the analysis of the temperature dependence of the I-V curves of different Pt/n-GaAs Schottky diodes two different groups could be identified. While the diodes of group 1 have a barrier height of about 1 eV which increases with decreasing temperature the diodes of group 2 have a barrier height of about 0.9 eV which is almost independent of the temperature. These findings are interpreted on the basis of recent models of Fermi-level pinning in Schottky diodes. The barrier height and the temperature dependence of the diodes of the first group are determined by the direct and indirect energy gap of GaAs. For the diodes of the second group defects pin the Fermi-level. Since their ionization entropy is almost independent of the temperature the barrier height is also temperature independent. The density of the defects is about one fiftieth of the total density of sites in a GaAs (100) plane. The results indicate that problems with impurities may have occurred during the processing of the devices. Furthermore it was found that the noise temperature is independent of the barrier height for a defect free Schottky contact while it depends on the magnitude of the spatial inhomogeneities at the Schottky contact. This study demonstrates that I-V-T measurements are useful not only to characterize the physical properties of a metal semiconductor transition but also to give useful information about the processing.

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Appendix: table 1 see next page

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Appendix

Tab. 1: Parameters of the investigated Schottky diodes.

Diode	Manufacturer	Doping Density [$10^{17}cm^{-3}$]	Ideality Coeff.	Zero-Bias Barrier Height [eV]	Flat-Band Barrier Height [eV]	Temperature Coefficient [meV/K]
SDO 20	Farran Tech.	0.5	1.28	0.830	1.048	-0.18
DA499	TU Darmstadt	1.0	1.12	0.917	1.017	-0.30
HSD3S	Tohoku U..	1.0	1.16	0.827	0.954	0.00
1T6	U. of Virg. (UVa)	1.0	1.39	0.758	1.040	-0.22
1I7 a	UVa	3.0	1.16	0.780	0.896	-0.01
1I7 b	UVa	3.0	1.34	0.777	1.037	-0.17
1I7 c	UVa	3.0	1.20	0.836	0.997	-0.27
1T12	UVa	3.0	1.22	0.821	0.990	-0.22
1I12	UVa	4.5	1.23	0.833	1.023	-0.21
1T14	UVa	10.0	1.67	0.544	0.917	0.02
1T15	UVa	10.0	1.57	0.628	0.990	-0.27