Modeling and Investigation of Instabilities in Heterojunction Interband Tunnel Diodes for Microwave Applications

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Abstract -- **The existence of Negative Differential Resistance (NDR) in tunneling diode has led to novel, quantum functional devices and circuits. The enhanced functionality of these devices enables design of both digital and analog circuits with reduced complexity, size and better performance. For many of these applications, the study of the stability criteria and the development of comprehensive CAD model is of great importance for both the design and the development of new devices. In this paper we present the results of the modeling and investigation of instability for InGaAs\InAlAs\InGaAs tunnel diodes having different dimensions. Experimental results, which confirm the conclusions, are presented.**

I. INTRODUCTION

Recently tunnel diodes have received a lot of attention in the microwave and analog high-speed field. The enhancement in the semiconductor growth techniques, in particular MBE, have lead to improved device quality and performance and also introduced new families of tunnel diodes. One family is based on intra-band resonant tunneling in semiconductor conduction band (RTD). Another family consists of Heterojunction Interband Tunneling Diodes (HITDs). These HITDs are interesting because of the high peak-to-valley current ratios and a large span of the negative differential resistance region. Tunnel diodes have been used to demonstrate numerous applications and potential markets including digital to analog converter, clock quantisers, shift registers and ultra low power SRAM [1]. All those application take benefit from the bi-stable inherent diode behavior and utilize the negative differential resistance (NDR) to increase the transition speed between the two stable states. In the microwave realm, although tunnel diodes in theory promise medium noise amplifiers, low noise converters, and low-cost oscillators, these circuits have never achieved the high volume of usage, which one would have expected on the basis of the claims being made [2]-[4]. Primarily this is because of the low power handling capability of the tunnel diode and the stability issues.

Many researchers have discussed the general problem of tunnel diode stability and tunnel diode based circuit stability [5]-[6]. In this paper the problem of characterization of an HITD which is inherently unstable is considered. We also investigate whether a particular modification of diode parameters could allow stable HITD operation in the NDR region. It is shown that for large diodes the embedding structure, which is normally composed of G-S-G pads and the transmission lines, along with the diode parasitic, can induce instability and consequently make the problem of diode characterization difficult.

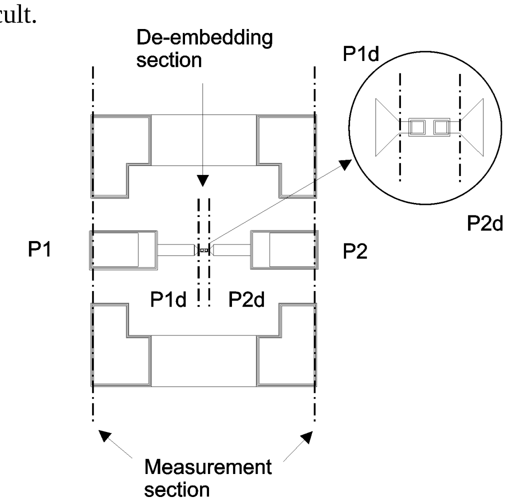

Fig:1: Test-set layout of the microwave HITD

A simple and reliable technique, based on the device physics consideration, for HITDs characterization is presented. The paper is organized as follows. The stability conditions for HITDs are recalled and discussed in section II. An equivalent circuit model for an unstable diode is identified and the critical parameters inducing instability are shown. A comparison between stable and unstable diode, on the basis of their equivalent circuit is presented. In section III it is shown that the embedding impedance plays a role in the instability. Validation of the theory is accomplished by experimental results.

II. STABILITY ANALYSIS

Fig. 1 shows the test-set layout of a microwave HITD. It is consists of G-S-G pads and a couple of transmission lines required to contact the diode. Figure 2a shows the equivalent circuit. The HITDs considered in the present work, consist of a 500Å, p+ (Carbon) doped InGaAs top contact layer, followed by a 500Å p+ doped InAlAs layer and finally a 1000Å n+(Silicon) doped InGaAs bottom contact layer. These heterostructure interband tunnel diodes have a square foot-print and have shown very high current densities (50-60KA/cm^2) and peak to valley current ratios

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between 10 and 15[2]. Analysis of microwave performance shows a maximum frequency of oscillation around 40GHz for a 2.5x2.5μm^2 tunnel diode.

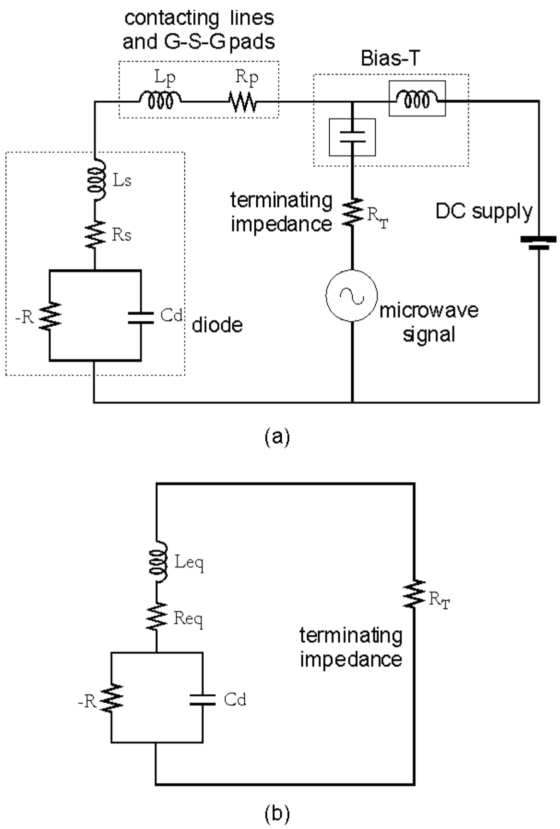

Fig. 2: a) Schematic circuit of the measurement test-set, b) Small-signal equivalent circuit

The analysis of the diode stability can be conducted in an effective way by reducing the above equivalent circuit to the one reported in Fig. 2b [5]-[6]. The impedance of the network as a function of the complex frequency, s=σ+jω is given in (1):

$$Z(s)=\left\{s^2 L_{eq} C_d R + s\left[\left(R_T+R_{eq}\right)RC_d - L_{eq}\right. + \left.\left[R-\left(R_T+R_{eq}\right)\right]\right\} \Big/ \left(sC_d R-1\right) \quad (1)$$

From the theory of the stability of a network, it is necessary that Z(s) have no zeroes in the right half of the s plane. Thus, both of the following conditions must be satisfied:

$$R > R_T + R_{eq} \quad ; \quad \left(R_T+R_{eq}\right)RC_d > L_{eq} \qquad (2)$$

The first equation of (2) relates the slope of the load curve and the diode dynamic resistance in the NDR region. If the condition is not satisfied then it is possible to have more than one intersection between the two curves. This leads to three possible bias points and consequently to an unstable behavior. For that reason this condition is also called the 'switching' condition. The second equation of (2) relates the negative resistance and the reactive component of the embedding circuit. If it is not satisfied then it leads to oscillations. Hence it is also referred to as 'oscillation' condition .

III. EXPERIMENTAL RESULTS

Fig. 3 shows the two current-voltage (I(V)) characteristics measured from two diodes sample having different sizes namely 2.5x2.5μm^2 and a 5x5 μm^2 (curves with symbols). The instability of the larger diode are quite evident and assume the shape of a plateau in the I(V) plane. It is worth noting that this isn't a unique way in which the diode instability is detected. In fact a switching behavior may also be observed which is typical for larger diodes.

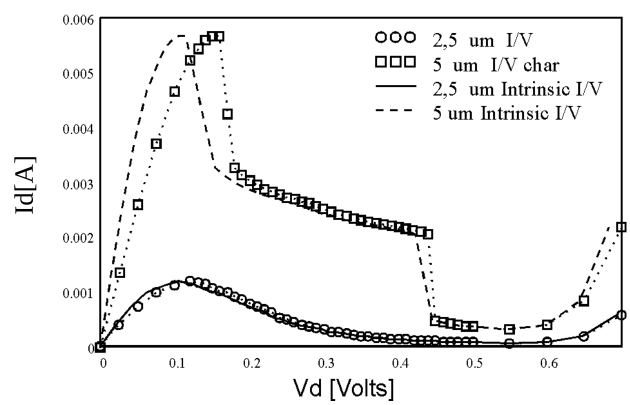

Fig. 3: Comparison between measured and intrinsic I\V characteristics for the 2.5x2.5μm^2 and 5x5μm^2.

The first step in the identification of the diode model consists of the evaluation of the series resistance (Rs). Although it may be small in magnitude (few ohms) and at high frequency could be neglected in comparison to other parasitic effects, its value assumes a critical role in diode stability. There isn't a unique approach for the determination of series parasitic resistance. In many works a fitting between measured and simulated RF data is the approach. In this work an additional assumption is made: diodes of different sizes should have the same intrinsic peak voltage, Vp. This consideration arises form the diode physics which stipulates that the peak in current is reached when the electron and hole wave functions in the n- and p-semiconductors have maximum overlap [7]. Practically extrinsic Vp is different for different sized diodes because the product of peak current and series resistance, Ip*Rs, is different for the diodes of different sizes. In our experiment, the best fitting between DC curves give values of 13Ω and 8Ω, for the 2.5x2.5 μm^2 and a 5x5 μm^2 diodes respectively. Due to the non-ideal fabrication process these values are not scaled by a factor proportional to the diode size. In Fig. 3 we report the I(V) characteristics of the intrinsic junction diode.

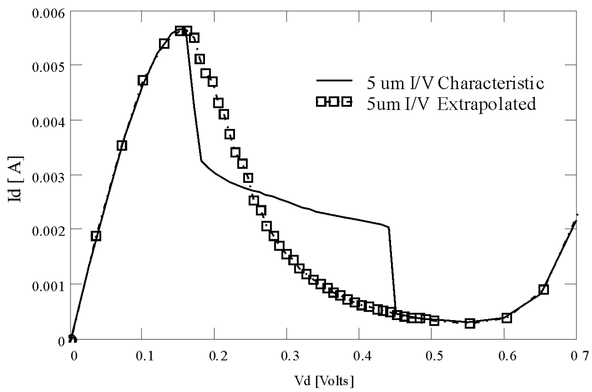

Fig.4 : Comparison between measured (continuos) 5x5μm^2 HITD and extrapolated (symbols) I\V characteristics

In order to ensure diode stability, the equations (2) must be verified. For that purpose an evaluation of the negative resistance is necessary and can be obtained by differentiating the intrinsic DC curve. While for the smaller diode that can be easily accomplished, the discontinuity in the DC curve of the larger diode doesn't allow any evaluation. To circumvent the problem, a further assumption is made here that the two intrinsic I(V) must be related only by a scaling factor. That way it is possible to estimate the continuous intrinsic I(V) of a 5x5μm^2 diode by multiplying the I(V) of the 2.5x2.5μm^2 diode by a proper constant. This is a good assumption because the discontinuous measured behavior is only due to instability so if the diodes were stable the DC curves should be scaled by their size.

TableI: equivalent circuit parameters for the HITDs

	2.5x2.5μm^2	5x5μm^2
Cd [pF]	0.085	0.34
Ls [nH]	0.1	0.5
Rs [Ω]	13	8
Lp [nH]	0.36	0.36
Rp [Ω]	1.3	1.3

The extrapolated curve can be differentiated to calculate the negative resistance in the NDR. Fig. 4 shows the comparison between the measured and the extrapolated I(V) for the 5um diode. In the latter the contribution of the series resistance Rs has been reintroduced for comparison. The circuit elements described in the equivalent circuit of Fig. 2a are evaluated by comparing the measured admittance matrix obtained by transforming the measured scattering matrix and the admittance matrix in symbolic form. These parameters are independent of the bias voltage except for the junction resistance, R. For the junction capacitance this is to some extent an assumption, however it has been found experimentally that its value is fairly constant in the voltage range of interest for the diode. The parameters R_P and L_P are due to the contacting structure and are evaluated by performing an electromagnetic simulation of that part of the structure [8]. The procedure described above leads to the value for both the diodes listed in table I.

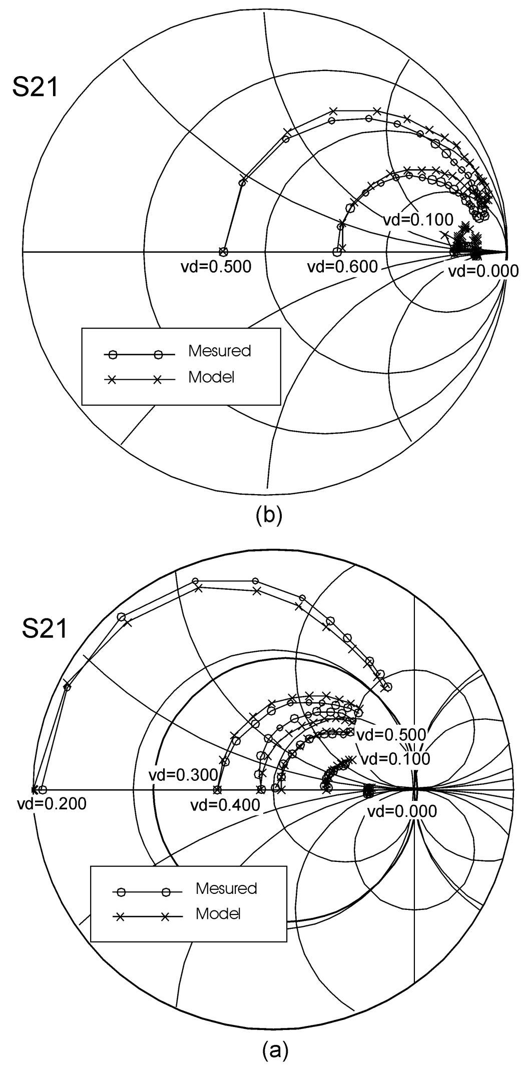

Fig.5: Comparison of the measured and simulated S21 parameter a) 2.5x2.5μm^2 , b) 5x5μm^2. Only for the smaller diode the comparison is also in the negative slope region.

The comparison between measured and simulated S21 parameters are reported in Fig. 5 for the bias points where the diodes are stable. This comparison validates the model. Since the most critical point is where the negative resistance assumes its minimum, R_{min} given by:

$$R_{\min} = \min \left| \left[\frac{dI_d(V_d)}{dV_d} \right)^{-1} \right|_{V_d = NDR} \quad (3)$$

the stability condition are tested assuming for R_{min}. We obtained values of -170Ω and -32Ω for the diodes 2.5x2.5μm^2 and a 5x5μm^2 respectively. Considering a generic system impedance R_T, the stability conditions in (2) can be re-written as:

$$\frac{L_{eq}}{R_{\min} C_d} < R_T + R_{eq} < R_{\min} \qquad (4)$$

We obtain for the 2.5x2.5μm^2 diode:

$$30\Omega < R_T + 14.3\Omega < 170\Omega \qquad (5)$$

This is satisfied for a system termination, R_T, ranging from 16Ω to 155Ω. In the contrary for the 5x5μm^2 diode:

$$36\Omega < R_T + 9.3\Omega \quad ; \quad R_T + 9.3\Omega < 32\Omega \qquad (6)$$

Thus the stability conditions are not satisfied for the 5x5 μm^2 diode. In conclusion the stability behavior observed for the smaller diode is confirmed by the calculation, in particular, under the hypothesis of 50Ω system impedance, there is also a stability margin of 70%.

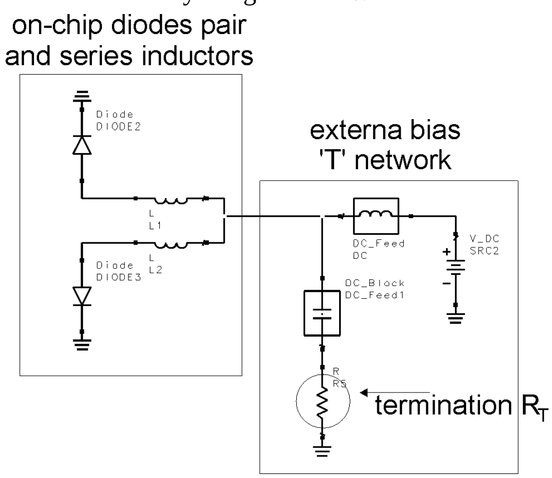

Fig. 6: Test circuit used to validate the stability criteria

For the larger diode the calculation shows that the instability can be avoided if the system impedance was reduced to value lower than $R_{\min} - R_{eq}$, and in the mean time the ratio L_{eq}/C_d was reduced by a factor $R_{\min}\left(R_T + R_{eq}\right)$. That constraint is of great importance for the circuit design and for the device optimization.

Now we discuss the experimental validation of the stability behavior with respect to the system impedance. Fig. 6 shows a test circuit involving a 2.5x2.5μm^2 diode pair and an inductor placed in series with each diode. The circuit is realized on the same wafer that contains the diodes of the above dissertation, so that the same equivalent circuit can be adopted. The series inductors have a nominal value of 0.84nH (with ~1ohm of series parasitic) so the stability conditions changes appropriately as:

$$58\Omega < R_T + 15\Omega < 170\Omega \qquad (7)$$

Fig 7 shows measured I(V) characteristic with different R_T. The figure shows the evident lack of stability for values of R_T less then 50Ω and higher then 90Ω as predicted by (7). This is an *a posteriori* confirmation of the theory.

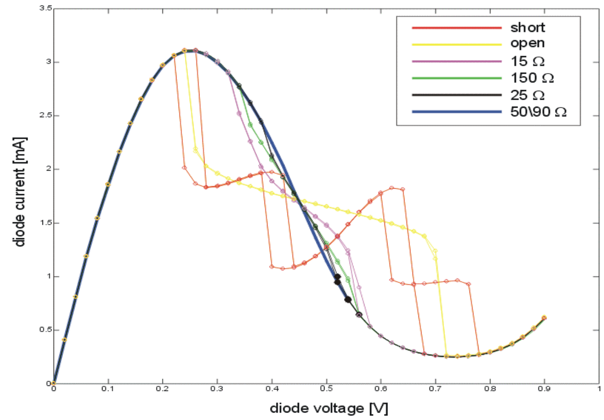

Fig. 7: Comparison of different I\V characteristic measured with different termination resistance R_T

IV. CONCLUSION

In this paper an effective technique to analyze the tunnel diode stability has been discussed and validated through static and small signal measurement. The investigation provides evidence for the importance of a proper diode termination and a tight control of parasitics to ensure stability of tunnel diode operation. The diode parameters have been quantitatively evaluated for InGaAs\InAlAs\InGaAs HITDs having different sizes developed for microwave applications.

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