E-7-4
Extended Abstracts of the 2015 International Conference on Solid State Devices and Materials, Sapporo, 2015, pp802-803

S-Parameter Characterization and Lumped-Element Modelling of mm-Wave Single-Drift IMPATT Diode

W. Zhang[1] and Y. Yamamoto[2], M. Oehme[1], K. Matthies[1], B. Tillack[2,3], E. Kasper[1], J. Schulze[1]

[1] University of Stuttgart, Institute of Semiconductor Engineering (IHT)
Pfaffenwaldring 47, D-70569, Stuttgart, Germany
Phone: +49-711-685-68011 E-mail: zhang@iht.uni-stuttgart.de
[2] IHP Microelectronics
Im Technologiepark 25, D-15236, Frankfurt (Oder), Germany
Phone: +49-335-5625-156 E-mail: yamamoto@ihp-microelectronics.com
[3] Technical University of Berlin, Einsteinufer 25, D-10587, Berlin, Germany

Abstract

Mm-wave single-drift impact avalanche transit-time (IMPATT) diodes were grown by using reduced-pressure chemical vapor deposition (CVD) and processed with silicon-based monolithic mm-wave integrated circuits (SIMMWIC) technology. The IMPATT-behavior was evaluated with small-signal S-parameter measurement up to 110 GHz. The avalanche frequency follows roughly $\sqrt{J}$-proportionality as proven for all samples. Samples within a small process window exhibited large negative differential resistance around avalanche frequency, which is the base for mm-wave amplifier and oscillator applications. A broad-band lumped-element model shows good agreement with the measured data and explains the overall principle for the functionality of selected samples.

1. Introduction

As the most powerful source for mm-wave band, the IMPATT diode has been widely employed in discrete form for microwave power generation [1] since the concept was proposed in 1950s [2]. Due to progress of technology integration [3], the implementation of monolithic IMPATT components like oscillator [4] or even transmitter [5] becomes more and more attractive. By using reduced-pressure CVD technique five p^{++}-n^{-}-n^{++} samples with variation of doping concentration in n^{-} layer were grown and fabricated as monolithic single-drift IMPATT diodes in this work.

2. Small-Signal S-parameter Characterization

According to the small-signal analysis proposed by Read [2] and developed by Gilden and Hines (G&H) [6], the avalanche frequency of the IMPATT diode is defined as:

$$f_{avalanche} = \frac{1}{2\pi}\sqrt{\frac{2v_S\alpha'}{\varepsilon}}\sqrt{J} \qquad (1)$$

, with v_S the saturation drift velocity of the carriers, α the ionization coefficient, α' is its derivative with respect to electrical field, ε the permittivity of the material, J the current density. After the proper de-embedding procedure for one-port device [7] the side effect of contact pads can be well compensated, thus only the S-parameters of embedded IMPATT diode were extracted from raw measured data. The obtained S-parameters of IMPATT diode were then transformed to impedance and expressed as real- and imaginary-part in frequency domain (Fig.1 blue & red curves). $f_{avalanche}$ in this case reaches ~ 90 GHz, at which real-part shows a maximum resonance (nearly -700 Ω), imaginary-part equals zero, respectively.

Additionally $f_{avalanche}$ should be proportional to $\sqrt{J}$ with constant v_S and α'(Fig. 1 grey line). However this proportionality is limited in reality by increasing temperature, which degrades both v_S and α'(Fig. 1 pink curve).

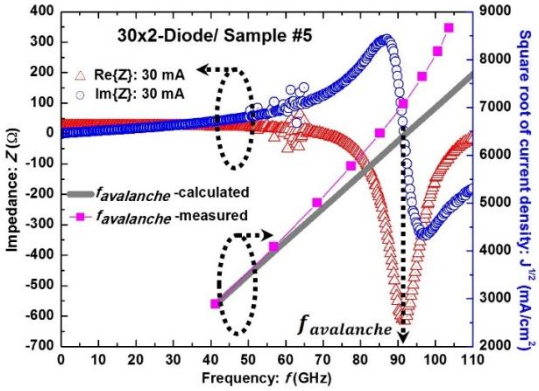

Fig. 1 From S-parameters extracted Re{Z} and Im{Z} spectrums of a 30x2 μm^2 IMPATT diode (Sample #5; 30 mA biasing) (left); Calculated & measured $f_{avalanche}$ vs. $\sqrt{J}$ (right).

3. Experimental and Modelling Results

Carrier concentration results in n^{-} layer

Capacitance-Voltage (CV) measurements were performed for all five samples to verify the carrier concentration level and layer thickness in n^{-} layer (Table I).

Table I: n^{-} Layer CV & S-parameter (till 110 GHz) Evaluation

Samp.	Carrier Concent. (cm^{-3})	Layer Thickness (nm)	Negative Resistance?
#1	1.0e17	325	No
#2	1.2e17	335	No
#3	1.4e17	325	Yes
#4	1.7e17	325	Yes
#5	2.2e17	325	Yes

Fig. 2 shows the depletion situation at breakdown voltage V_b of IMPATT diode with certain n^{-} thickness and different doping concentrations. The distribution of avalanche-and drift-region together with physical thickness of the total n^- layer decides the functional frequency range of the IMPATT diode.

Two reasons for Sample #1 & #2, which didn't show negative resistance up to 110 GHz at all, can be explained. Firstly low doping concentration leads to high V_b, which limits the maximum biasing current by the same DC power load. This means, the device can be driven without damage only up to certain frequency due to its limited thermal load. On the other hand, too low doping concentration (Fig. 2 red solid line) shifts the space charge region (SCR) out of the total layer thickness, thus enlarges avalanche-region and shrinks drift-region within limited layer thickness. This forces the functional IMPATT behavior only in even higher frequency range, which can be never achieved due to limited thermal load of the device.

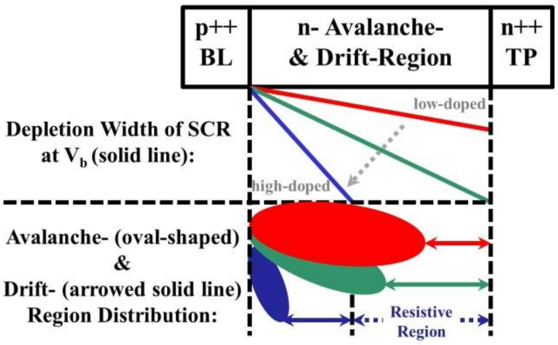

Fig. 2 Depletion situation at V_b & distribution of avalanche- & drift-region with different doping concentrations and thickness of n^- layer.

Broad-band lumped-element modelling

To understand the functionality of IMPATT diode, a broad-band lumped-element model has been developed (Fig. 3). R_S represents the series resistance and can be extracted from diode I-V characteristics. C_j is junction capacitance and obtained from C-V measurement. C_j with junction inductance L_j defines the $f_{avalanche}$ together. R_L summarizes all extra resistive losses, which occur by the avalanche- and drift-mechanisms. The conductance G is in this model always negative, which describes the gain effect due to certain avalanche- and drift-mechanisms, thus relevant for modelling of negative differential resistance.

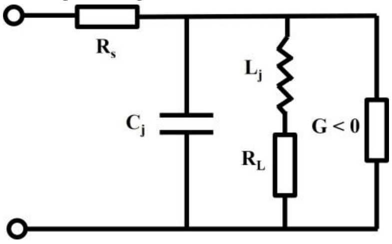

Fig. 3 The developed lumped-element model of IMPATT diode.

The developed lumped-element model was applied on Sample #3, #4 and #5, which showed negative resistance by S-parameter characterization with certain biasing. Good agreement between measurement and modelling of selected samples indicates the reliability of the model (Fig. 4).

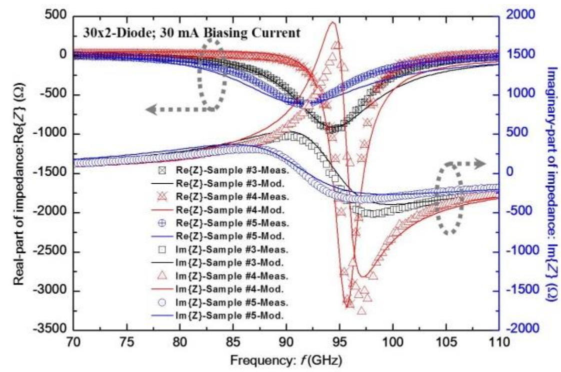

Fig. 4 Measurement vs. modelling for 30x2 μm^2 diodes on Sample #3, #4 and #5 with the biasing current 30 mA.

4. Conclusions

S-parameter characterization was performed for five single-drift IMPATT samples, fabricated with reduced-pressure CVD technique and monolithic technology. The $\sqrt{J}$-proportionality related to $f_{avalanche}$ with and without temperature effect are experimentally observed and explained. A theoretical analysis based on depletion situation and distribution of avalanche- & drift-region with different doping and certain layer thickness was given. Together with the limited thermal load of the device, the appearance condition of negative resistance behavior could be explained. Good agreement between measurement and modelling on Sample #3, #4, #5 shows that the developed lumped-element model can describe the functionality of IMPATT diode straightforward in a broad-band manner.

Acknowledgements

The authors wish to acknowledge Sabine Rohmer for the support of photolithograph process in-house. Thanks are due to Wolfgang Kasper and Martin Model from Anritsu for support and discussion about measurement setups.

References

[1] Thomas H. Lee, *Planar Microwave Engineering: A Practical Guide to Theory, Measurement and Circuits*, (2004) 296.

[2] W.T. Read Jr., *A proposed high-frequency negative resistance diode*, Bell Syst. Tech. J., **37**, (1958) 401.

[3] E. Kasper, M. Oehme, "*IMPATT diodes" in, Si Heterostructure Handbook: Matrials, Fabrication, Devices, Circuits, and Applications of SiGe & Si Strianed-Layer Epitaxy,* (2006) 661.

[4] J. Hasch and E. Kasper, *S-parameter Characterization of mm-wave IMPATT oscillators*, Silicon Monolithic Integrated Circuits in RF Systems, (2006).

[5] T. Al-Attar and T. H. Lee, *Monolithic Integrated mm-wave IMPATT Transmitter in Standard CMOS Technology*, IEEE Trans. on Microwave Theory & Techniques, **53**, (2005) 3557.

[6] M. Gilden and M.E.Hines, *Electron tuning effects in the Read microwave avalanche diode*, IEEE Trans. Electron Devices, **13**, (1966) 169.

[7] H. Xu, E. Kasper, *A De-embedding Procedure for One-Port Active mm-Wave Devices*, 10th Topical Meeting on Silicon Monolithic Integrated Circuits in RF Systems, Digs.(2010) 37.