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CHARACTERIZATION OF AVALANCHE PHOTODIODE PROPERTIES IN FREQUENCY DOMAIN

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Abstract

Avalanche photodiodes (APD) are promising optoelectronic components for optical communication systems. This article deals with characterization of APD properties from microwave S-parameter measurements. Basic parameters of APD based on InGaAs/InP structure were measured in frequency domain using microwave vector network analyzer (VNA) HP8408B. Acquired data was used for determination of basic APD parameters as well as identification of small signal photodiode model. For this purpose the simplex optimization method was successfully employed.

1 INTRODUCTION

Photodetectors are crucial part of optical communication systems, which are so important for human life. APD belongs to perspective photodetector types due to high gain caused by photo-generated carrier multiplication. Well-designed APD can be used in high sensitivity and wide bandwidth optoelectronic receivers. This article deals with characterization of properties of SACM (Separated Absorption, Charge and Multiplication) APD. The methodology for modulation frequency response measurement and microwave reflection coefficient measurement in frequency domain utilizing HP8408B VNA is presented. Modulation frequency bandwidth was determined directly from measured response. Different small-signal equivalent circuits of output impedance for different bias points were extracted employing simplex optimization method. Identified model is compared with low-frequency C-V measurements. APD structure, measurement methodology and obtained results are described in more details below.

2 APD STRUCTURE

The layer structure of the fabricated mesa SACM APD is shown in Fig. 1. It consists of six epitaxial layers grown on a $\langle 100 \rangle$ - oriented, S-doped InP substrate. The device design determines electric field sufficiently high within the InP multiplication layer to support the avalanche multiplication and low enough in the small bandgap InGaAs absorption layer to prevent interband tunneling and impact ionization. To maximize the gain-bandwidth product, the thickness of multiplication region was kept as minimum as possible to minimize carrier transit time.

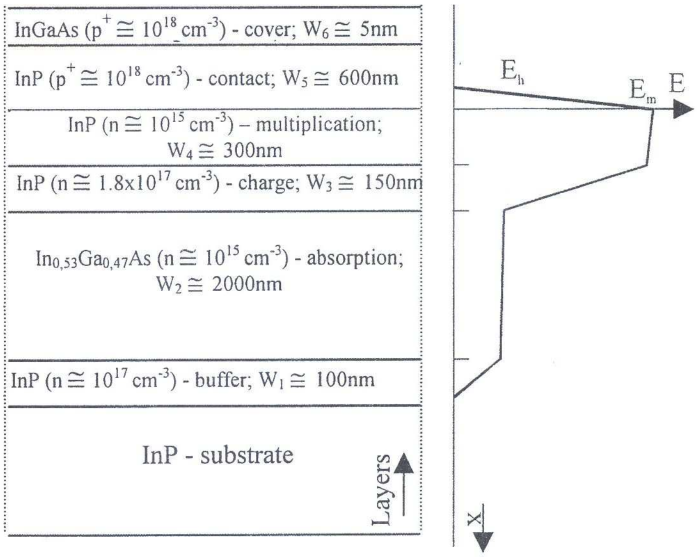

Fig. 1: Schematic diagram of tested SACM APD layer structure with electric field profile.

3 FREQUENCY DOMAIN MEASUREMENTS

The HP8408B VNA was adapted for investigation of SACM APD properties in frequency domain. Simplified block diagram of experimental set-up for modulation frequency response measurement (S_{21OE}) is shown in Fig. 2. High frequency signal from sweep oscillator HP8350B is splitted into measurement and reference path. The output measurement signal modulates a laser diode light in HP83422A Lightwave Modulator (λ=1308 ± 10nm, Pmax=600μW). Modulated optical signal from HP83422A is fed up to photodiode under test by the single mode optical fiber probe. Position of the optical probe can be moved in three directions by micropositioners in order to establish maximal optical power to measured sample. Tested photodiode converts optical signal to electric form. The microwave probe tip is connected to photodetector and it serves a dual purpose. It supplies photodetector from DC voltage source V_1 and it also feeds output microwave-modulated signal from structure under test to amplifier. The HP8410C Network Analyzer compares amplified microwave signal and reference signal from sweep oscillator HP8350B. Voltages at HP8410C output are related to amplitude ratio and phase shift between measurement and reference signals. They correspond to amplitude and phase of modulation frequency response. Both are converted to digital form by D/A converter HP59313A and transferred into personal computer via HPIB for additional processing.

Microwave reflection coefficient measurement (S_{22}) of APD using VNA HP8408B is the same as a measurement of any microwave one-port and was published in [1]. Additional information about calibration and measurement using HP8408B VNA with extension set for on-wafer measurements can be found in [2].

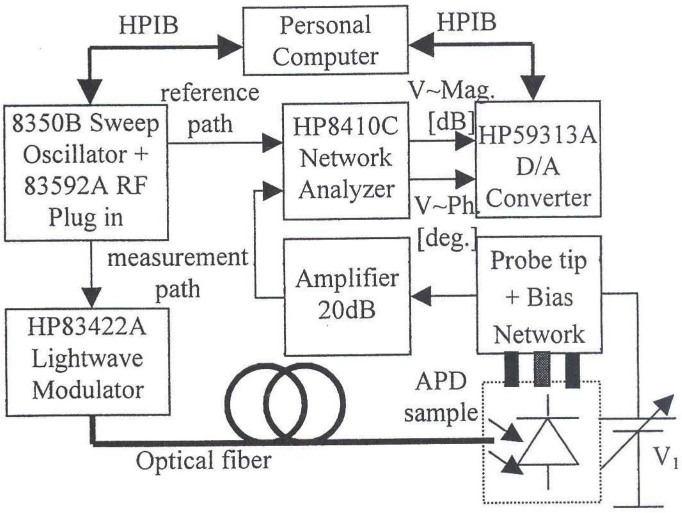

Fig. 2: The block diagram of experimental set-up for APD modulation frequency response measurement.

4 SMALL SIGNAL MODEL PARAMETERS IDENTIFICACTION

The equivalent circuit of investigated APD can be composed from two main parts. A current source which models the photocurrent generated in the photodetector by incident light (it may include dark current too) and output impedance, which models internal capacitances and resistances as well as parasitic effects. Complexity of equivalent circuit depends on demands for agreement between modeled and simulated characteristics as well as on the relation between circuit elements and physical parameters. Several photodetector equivalent circuits were tested in order to fit measured responses. Equivalent photodetector circuits in Fig. 3a) and 3b) are generally known, but they didn't approximate measured reflection coefficient well. Better results were obtained using equivalent circuit in Fig. 3c). It was created by modification of mentioned equivalent circuits. At the beginning of identification process the reflection coefficient S_{22c} was derived from chosen equivalent circuit. Then the simplex optimization method [3] was employed for evaluation of circuit element values by minimization of error function. The error function Q was calculated as deviation between calculated (S_{22c}) and measured (S_{22m}) complex reflection coefficients in wide frequency range.

$$Q=\sum_{i=1}^{n}\left|S_{22m,i}-S_{22c,i}\right| \qquad (1)$$

Optimization process was automated by implementation of simplex optimization method into program for automated S-parameter measurement and measured data processing [4].

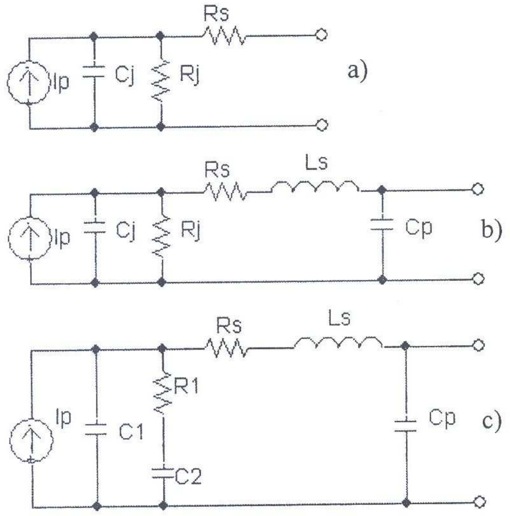

Fig. 3: Three different small signal APD equivalent circuits.

5 RESULTS

The modulation frequency response of investigated APD at various bias voltages is shown in Fig. 4. Measured curves are non-calibrated due to lack of calibration photodetector with required properties. It means that measured phase has no valuable information in this case. Hence it isn't included in results. Modulation frequency bandwidth was determined as 3dB amplitude drop of measured modulation frequency response. It was approximately 850 MHz at 30V bias voltage.

Small signal equivalent circuit parameters in Fig. 3c) were determined from microwave reflection coefficient measurements by methodology described in chapter 4. Parasitic elements C_p and L_s are negligible. It fulfills our expectation, because APD was on-wafer measured without bond-wire and package parasitics. Resistance R_1 has approximately 120Ω constant value. The R_s varies from 2.4Ω up to 3.7Ω with rising bias voltage from 0V up to 40V.

The microwave reflection coefficient of investigated photodetector at different bias voltages is shown in Fig. 5 and Fig. 6. Measured results show a good agreement between measured and calculated reflection coefficient. Output impedance is frequency and bias voltage dependent. Voltage dependency is caused by variation of depletion region width, which changes junction capacitance value. Comparison between measured junction capacitance and capacitances calculated from identified model is shown in Fig. 7.

6 CONCLUSION

The methodology for characterization of APD from microwave measurements in frequency domain has been described. VNA HP8408B was adapted for on-wafer optelectronic measurements. Several prototypes of SACM APD were measured. The modulation frequency bandwidth was determined. Chosen small signal model was identified for different bias voltages, which is a good starting point for future large-signal APD model development.

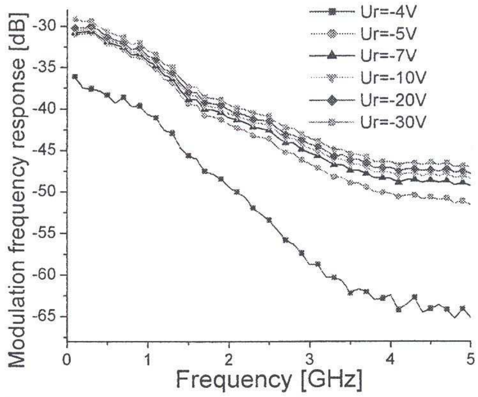

Fig. 4: Modulation frequency response of investigated APD for different bias voltages.

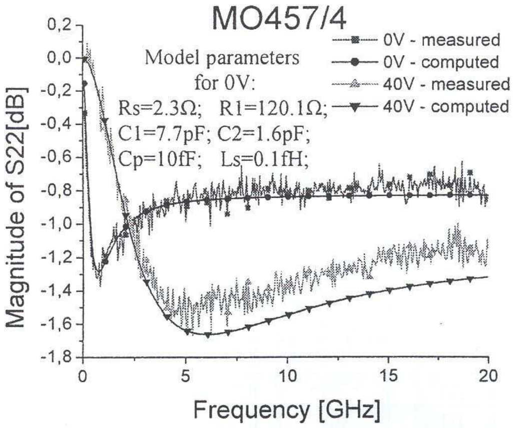

Fig. 5: Comparison between measured and computed reflection coefficient magnitude for different bias voltages.

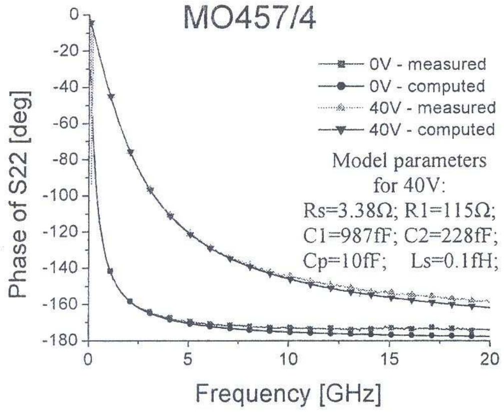

Fig. 6: Comparison between measured and computed reflection coefficient phase for different bias voltages.

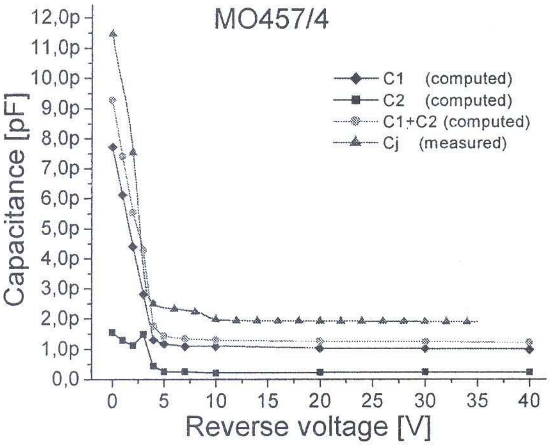

Fig. 7: Comparison between measured DC junction capacitance and computed capacitances from model.

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