MICROWAVE CHARACTERIZATION OF HIGH-SPEED PIN PHOTODIODES

A.HILT*°♦, G.JÁRÓ*, A.ZÓLOMY*, B.CABON°, T.BERCELI*♦, T.MAROZSÁK*

* *BME-MHT, Technical University of Budapest, Department of Microwave Telecommunications*
H-1111 Goldmann György tér 3. V2.ép VI.em., Budapest, HUNGARY
fax.: (+36 1) 463 32 89   tel.: (+36 1) 463 41 42, e-mails : hilt@nov.mht.bme.hu ,   jaro@nov.mht.bme.hu

° *LEMO-ENSERG-INPG, Institut National Polytechnique de Grenoble*
23 Rue des Martyrs, BP 257, F-38016 Grenoble, Cedex 1, FRANCE
tel.: (+33) 04 76 85 60 13, fax: (+33) 76 85 60 80, e-mails : cabon @ enserg.fr ,   hilt @ enserg.fr

♦ *TKI Rt., Innovation Company for Telecommunications, H-1142 Budapest, Ungvár u. 64-66, HUNGARY*
tel.: (+36 1) 251 08 88, fax: (36 1) 251 98 78, e-mails : berceli @ tki.hu ,   hilt @ tki.hu

Abstract : Optical responsivity and electrical reflection of an ultra high-speed pin photodiode (PD) are measured in 20 GHz frequency range. The effect of PD bias voltage variation was investigated at different incident optical power levels. Based on the measurements an equivalent circuit is developed by optimization. The effect of the bonding wires connecting the diode to the embedding circuit was also investigated.

I. Introduction

The increasing demand for microwave and millimeter-wave fiber-optic links requires high speed optical receivers. The general configuration consists of a transimpedance amplifier driven by a pin photodiode. The bandwidth of the optical receiver is limited either by the PD or by the external electrical circuit containing the matching network and the wideband amplifier. Recently photodiodes and amplifiers have been reported with extremely wide band operation [1,2]. However, matching the PD to the input impedance of the amplifier is one of the main restriction factors [3]. The direct connection using bond wires can be considered as the simplest matching circuit. Accurate microwave characterization of the PD is necessary for the proper design of the external electrical circuit. In this paper a PD chip model is given including parasitic elements. The effect of bias, optical intensity and bonding wires are also analyzed.

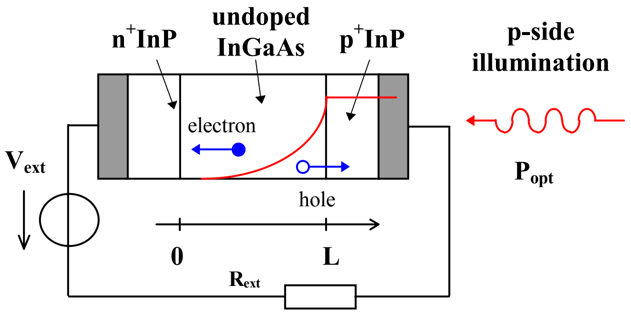
II. Response of pin-Photodiodes

The intensity modulated optical signal illuminating the PD is written in the form :

$$P_{opt} = P_0 \, (\, 1 + m \cos\omega t \,) \, , \qquad \text{(Eq.1)}$$

where ω is the angular frequency of the microwave modulation signal. At a given P_{opt}, the responsivity R of the pin photodiode is frequency and bias dependent [4] :

$$R(f, V_{PD})[\mathrm{dB(A/W)}] = 20 \log \frac{R[\mathrm{A/W}]}{1[\mathrm{A/W}]} \, . \qquad \text{(Eq.2)}$$



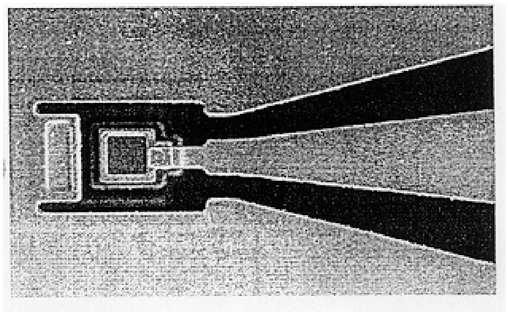


Figure 1. Schematic structure of the pin photodiode **Figure 2.** Opto Speed PD94CP-S12AR1300 pin PD chip

The simplified pin PD structure (without buffer layers) is shown in Fig.1. Frequency dependence of the optical response has been investigated by several authors [1,5,6,7,8,9]. The physical model is based on the generation and transport of charge carriers of the illuminated semiconductor device. Analytical solution for the frequency response of the pin PD is given by Bowers [5] (n-side illumination) :

$$H(\omega)=\frac{i(\omega)}{I_0}=\frac{1}{1-e^{-\alpha L}}\left[\frac{e^{j\omega\tau_n-\alpha L}-1}{j\omega\tau_n-\alpha L}-e^{-\alpha L}\frac{e^{j\omega\tau_n}-1}{j\omega\tau_n}+\frac{e^{j\omega\tau_p}-1}{j\omega\tau_p}+\frac{e^{-\alpha L}-e^{j\omega\tau_p}}{\alpha L+j\omega\tau_p}\right], \qquad \text{(Eq.3)}$$

where L is the thickness of the intrinsic layer, τ_n and τ_p are the transit times assuming saturated drift velocities, and α is the absorption coefficient.

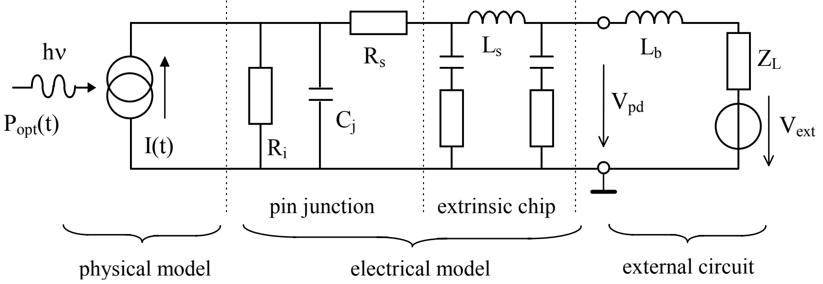


Figure 3. Model of the pin photodiode

The complete pin PD model is composed of the physical and the electrical model parts [6]. The physical model includes the transit time limit (Eq.3), other phenomena such as noise, trapping, thermal generation are usually neglected. The electrical model consists of the pin diode intrinsic chip model (junction capacitance, junction and series resistance), the extrinsic chip (e.g. bonding pad capacitance) and the external circuit, which is usually a 50 Ω load (Fig.3).

III. Experimental Characterization of a pin Photodiode

High speed pin photodiodes are frequently constructed with waveguide structure [1]. In our experiments the PD94CP-S12 chips were used, manufactured by Opto-Speed [10]. The active area of the PD is 12 x 12 or 16 x 16 μm^2, covered by antireflection coating layer. The tapered coplanar transmission line enlarges the contact pads to a pitch distance of 150 μm (Fig.2). The coplanar waveguide structure allows direct coplanar probe measurements [11]. Impulse response measurements using very short laser pulses have been performed by the manufacturer. Due to the small active area of the device rise and fall times are shorter than 18 ps, which correspond to a cut-off frequency higher than 40 GHz. (Time domain measurements are usually followed by an FFT to determine the frequency response.)

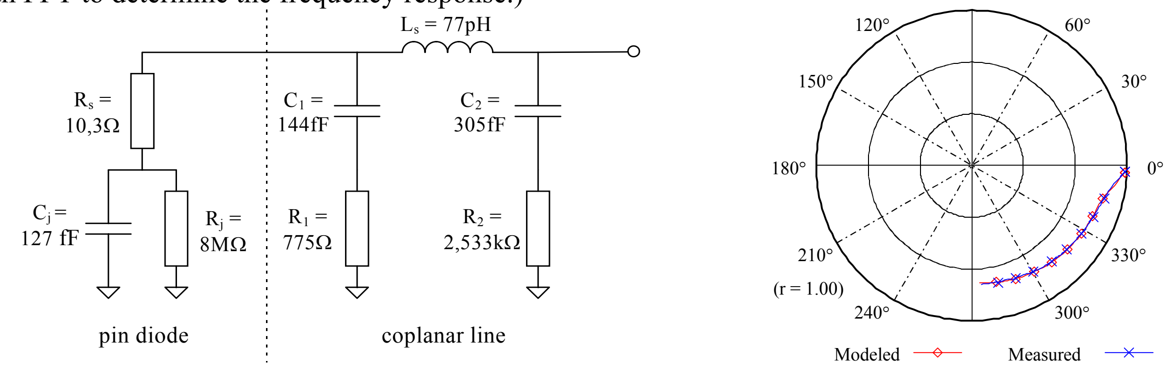


Figure 4. a) Equivalent circuit of the 16x16μm^2 pin PD **b)** Measured and the modeled reflection (Γ_{el}) of the chip

Our electrical model is based on frequency domain measurements and parameter extraction. For the optical and electrical characterization of the PD a HP 5610B Vector Network Analyzer was extended by a HP 83420A Lightwave Test Set (LWTS) [4]. The LWTS includes a Distributed FeedBack (DFB) laser source emitting at the wavelength of λ = 1,3 μm. The optical signal of the DFB laser is intensity modulated by an external Mach-Zehnder modulator. The optical modulation depth was m = 25 %, and the average optical intensity in the fiber was P_0 = 300 μW. This measurement configuration allows optical-to-electrical conversion measurements as well as electrical reflection measurements of an illuminated PD in the microwave frequency range.

The small signal equivalent circuit of the diode is shown in Fig.4 a). The model shows a good agreement with the measurement (Fig.4 b) (V_{ext} = -10 V, R_{ext} = 27 kΩ). Rj is in the order of a few MΩ, therefore its effect during the optimizations was negligible [1].

IV. Bias Dependence of Measured Optical Response

Fig.5 shows the measured responsivity using coplanar and coaxial measurement techniques, respectively. Applying higher reverse bias voltages, which results in higher electric field across the depleted region, the flatness of the response is improved due to the significant reduction of charge carrier transit times, as it is shown in Fig.5.

In Fig.5 b) the surface diagramme of the coaxial measurement shows the effect of bonding. The peak around 12 GHz and roll-off above 16 GHz is due to the inductance of the bonding wires ($L_b \cong 1{,}47$ nH). In the probe measurements shown in Fig.5 a) the obtained bandwidth was higher, and the roll-off was not observed in the frequency band of 20 GHz.

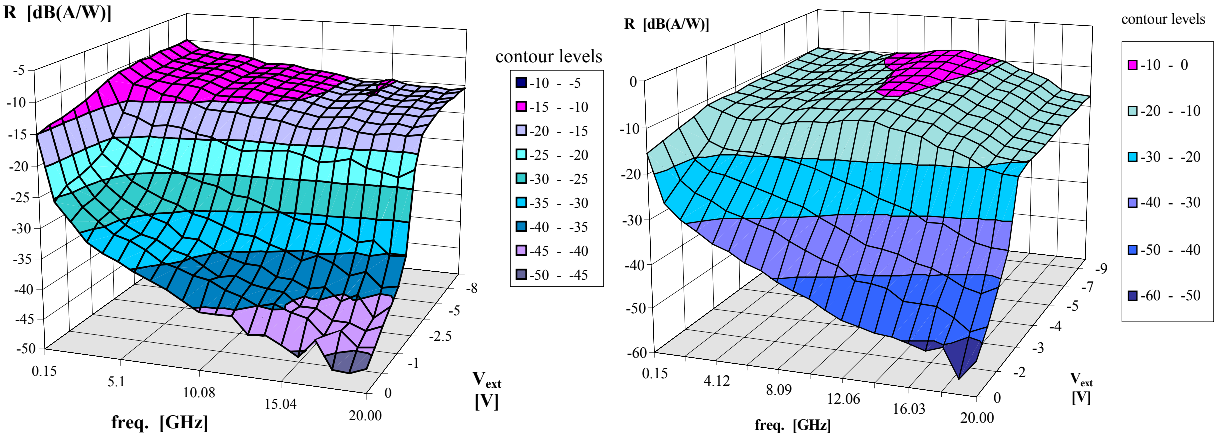


Figure 5. Optical response of 12 x 12 μm^2 Opto Speed pin PD as a function of frequency and bias
a.) coplanar probe measurement **b.)** bonded chip, coaxial measurement

V. Electrical Reflection of Bonded PD

Fig.6 a) shows the electrical reflection of a bonded pin PD as a function of bias voltage and frequency. Illuminating the active area by the laser beam, a significant change of the reflection coefficient is measured as it is illustrated in Fig.6 b) and c). This is due to the photocurrent I_L which changes the diode voltage V_{PD}. Even for negative external bias, the diode voltage can be positive under illumination if $I_{PD} < V_{ext} / R_{ext}$:

$$V_{PD} = V_{ext} - I_{PD} R_{ext} \quad \text{and} \quad I_{PD} = I_S(e^{qV_{PD}/kT} - 1) - I_L . \qquad \text{(Eq.4)}$$

Variation of V_{PD} alters the thickness of the depleted region and its C_j capacitance (Fig.7).

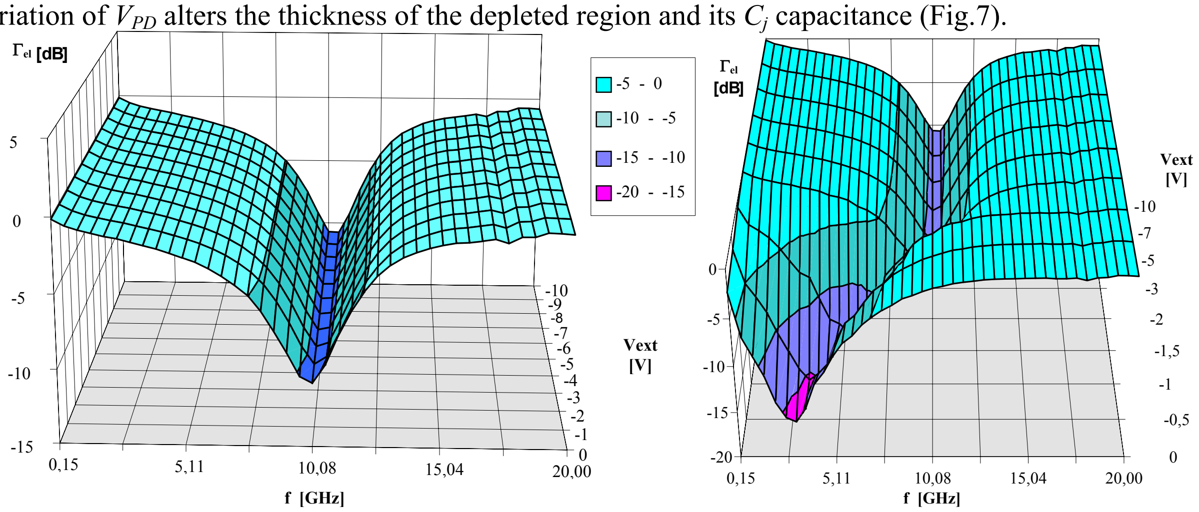


Figure 6. Measured electrical reflection of the bonded 16 x 16 μm^2 pin PD chip
a.) without optical illumination **b.)** with an incident optical power of P_{opt} = 140 μW

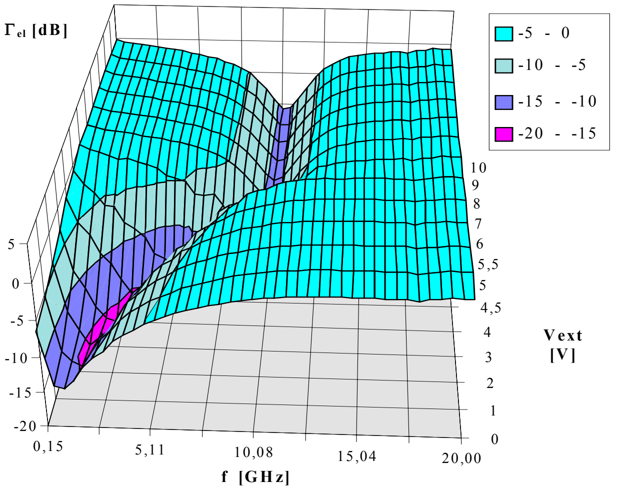


Figure 6 c.) with an illumination of $P_{opt} = 300\ \mu W$

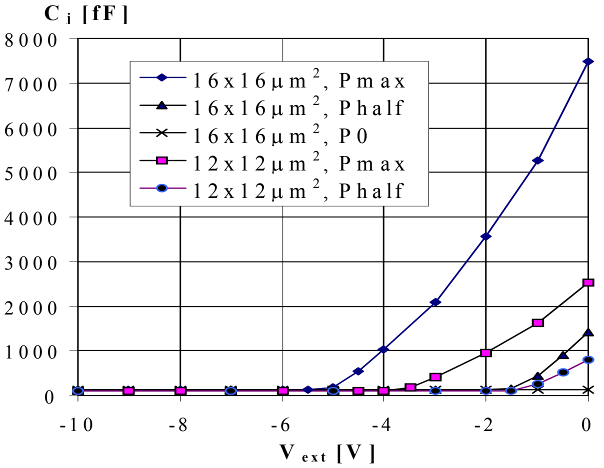


Figure 7. Junction capacitance as a function of external voltage and optical power ($P_{opt\ max} \approx 300\ \mu W$, R_{ext}=27 kΩ)

VI. Conclusions

The pin PD responsivity and electrical reflection presented a significant bias and optical power dependence. Using the measured S-parameter data an equivalent circuit of the high speed pin PD has been developed, including parasitics. Even at negative external voltages, the light induced photocurrent can inverse the polarity of the pin PD voltage resulting high junction capacitance and lower speed. The importance of strong reverse bias applied to the photodiode in order to achieve fast operation is emphasized. In this case the bandwidth is purely limited by the equivalent electrical circuit elements (diode model, bonding and load).

Acknowledgment

The authors wish to thank Prof.Colin S.Aitchison and Dr.R.Dall'Ara for the important discussions. The pin PD chip samples were provided by Opto-Speed SA. The work was supported by the 'COPERNICUS No.6665' and FRANS projects of the European Union and the Hungarian National Scientific Research Fund 'OTKA' No. F024113 and T 017295.

References

[1] Y-G.Wey, K.Giboney, J.Bowers, et al. : "110 GHz GaInAs / InP Double Heterostructure p-i-n Photodetectors", *Journal of Lightwave Technology, Vol. 13, No. 7, pp. 1490 - 1499,* July 1995.

[2] K.W.Kobayashi, L.T.Tram et al. : "Extending the Bandwidth Performance of Heterojunction Bipolar Transistor-Based Distributed Amplifiers", *IEEE Trans. on MTT, Vol.44, No.5,* May 1996.

[3] G.Járó, T.Berceli, A.Hilt, A.Zólomy : "Gain and Noise Optimization of an Optical Receiver Utilizing a Distributed Amplifier", *proc. of the ECCTD'97,* Budapest, Hungary, 30 August- 3 September 1997.

[4] HP 83420A Lightwave Test Set, Operating and Service Manual, Manual Part No. 83420-90001, March 1991.

[5] J.E.Bowers, C.A.Burrus, R.J.McCoy : "InGaAs PIN Photodetectors with Modulation Response to Millimetre Wavelengths", *Electronics Letters, Vol. 21, No. 18, pp. 812 - 814,* 29th Aug. 1985.

[6] A.Stolze, G.Kompa : "Nonlinear Modelling of Dispersive Photodiodes Based on Frequency- and Time-Domain Measurements", *proc. of the 26th EuMC, pp. 379-382,* Prague, Czech Republic, Sept. 1996.

[7] R.Sabella, S.Merli : "Analysis of InGaAs P-I-N Photo-diode Frequency Response*", IEEE Journal of Quantum Electronics, Vol. 29, No. 3, pp. 906-916,* March 1993.

[8] M.Makiuchi, M.Yano : "Flip-Chip Planar GaInAs/InP p-i-n Photodiodes Analysis of Frequency Response", *Journal of Lightwave Technology, Vol. 14, No. 1,* Jan. 1996.

[9] T.Berceli, B.Cabon, A.Hilt, G.Járó : "Improved Optical-Microwave Mixing Process Utilizing High Speed Photo-diodes", *proc. of the 26th EuMC, pp. 125-129,* Prague, Czech Republic, Sept. 1996.

[10] Opto-Speed S.A. : "PD94CP-S12AR1300 InGaAs pin photodiode chip data sheets", Via Cantonale, Mezzovico, CH - 6805 Switzerland, January and November 1995.

[11] Hewlett-Packard Product Note 8510-6 : "On-wafer measurements using the HP 8510 Network Analyzer and the Cascade Microtech wafer probes", 5954-1579, May 1, 1986, and "HP 8510B Network Analyzer, System Manual".