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Microwave Nonlinearities in Ge/Si Avalanche Photodiodes having a Gain-Bandwidth Product of 300 GHz

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Abstract: The nonlinearity of a 300 GHz gain bandwidth Separate Absorption Charge Multiplication (SACM) Ge/Si avalanche photodiode was examined experimentally for varying multiplication factors. The maximum second order dynamic range was 84.8 dB·Hz$^{1/2}$. The largest third order dynamic range was 101.5 dB·Hz$^{2/3}$.
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1. Introduction

Avalanche photodiodes (APDs) are strong candidates for use in fiber optic receivers when input optical power is likely to be low because of their high sensitivity and adjustable gain. At telecommunications wavelengths, III-V APDs have traditionally been used, but they are impractical in very high speed applications because of their low gain-bandwidth product (~100 GHz) [1].

Silicon-multiplication-region APDs represent a promising alternative to III-V APDs [2,3]. The low electron and hole ionization coefficients ratio in Si ($k < 0.1$) allows for high gain bandwidth products and low excess noise factors. Since Si is not responsive at telecommunications wavelengths, a suitable material for the absorption region must be found. Ge is one such material that has acceptable responsivity at telecommunication wavelengths. In this paper we measure the linearity of high gain bandwidth product SiGe APDs and examine their suitability for analog applications.

The analog characteristics of receivers are important for a variety of applications, including antenna remoting, subcarrier multiplexing (SCM), and frequency division multiplexing (FDM). Second- (IMD2) and third order intermodulation distortion (IMD3) limit performance and must be minimized to avoid interference with other channels. In this work, we demonstrate a high-bandwidth Ge/Si APD with a second order spur-free dynamic range (SFDR) of 84.8 dB·Hz$^{1/2}$ and third order SFDR of 101.5 dB·Hz$^{2/3}$. We also perform the first experimental study of the effect of multiplication factor on linearity.

2. Device structure and DC characteristics

The Ge/Si APD presented here consists of absorption and multiplication regions separated by a charge layer that controls the electric field as shown in Figure 1. Absorption and multiplication take place in Ge and Si, respectively. The 80-µm-diameter device has a reverse breakdown voltage, defined here as the voltage at which the dark current reaches 50 µA, around -24 V.

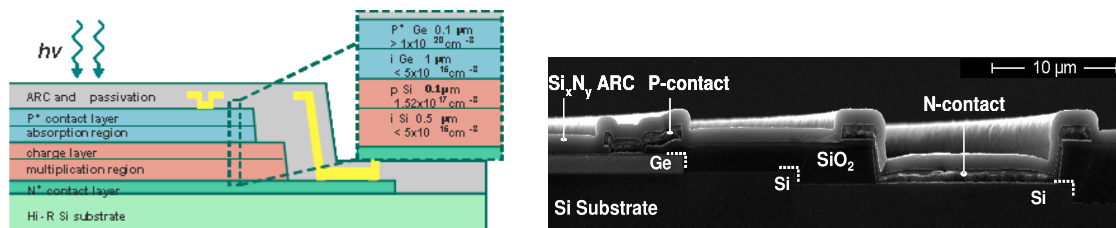

Fig. 1. a) Device structure. b) SEM cross-section.

The primary responsivity at 1550 nm, which was measured using a *p-i-i-n* device fabricated on the same wafer, is 0.24 A/W. The gain was obtained by normalizing the responsivity to the primary responsivity. At -20 dBm input optical power, the gain ranges from 4.2 to 33 between 21 and 25.5 V reverse bias. Figure 2a) shows the dependence of photocurrent on input optical power at several bias voltages. Because the microwave frequency nonlinearity was examined at an average input optical power

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of -20 dBm, the linearity of the curve in Figure 2a) around this point is of particular interest. Figure 2b) shows the percent deviation from the photocurrent predicted by the responsivity of the APD at -20 dBm. The rolloff at high gain and high input powers is due to the reduction of internal electrical field in the gain region due to the finite resistance.

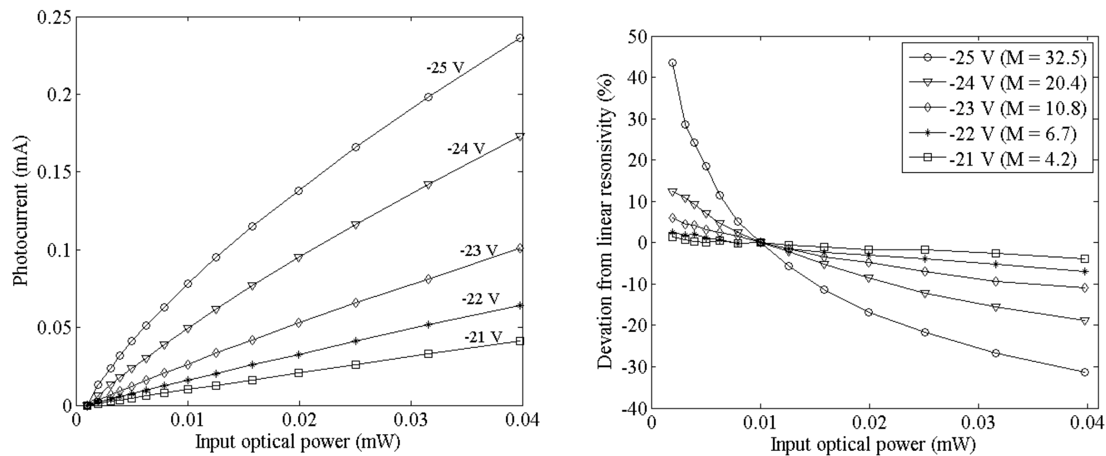

Fig. 2. a) Photocurrent for varying input optical power at several reverse bias levels at a wavelength of 1550 nm.

b) Deviation from linear responsivity at -20 dBm for varying input optical power at several reverse bias levels.

3. Microwave frequency nonlinearity

The microwave frequency linearity of the APD at 1550 nm and an average input optical power of -20 dBm was examined using a two-tone setup [6]. Tones were generated at 1 and 1.005 GHz. The modulation depth was varied between 30% and 70%. Figure 3a) shows IMD2 measurements and -23 V bias. The photocurrent is 30 µA, the gain is 10.8, the second order intercept point (OIP2) is -9.9 dBm and the SFDR is 84.8 dB·Hz$^{1/2}$. Figure 3b) shows the second order dynamic range of the photodiode as a function of gain. Above a gain of 10.8, the microwave frequency linearity behaves as predicted by the DC linearity in Figure 2b. The increase in SFDR with voltage below this point is similar to the behavior of a PIN, where the larger electric fields make the device less sensitive to space charge effects. The rapid decrease in SFDR at high gains is likely due to the large amplified photocurrents and greater sensitivity of the gain to voltage at higher voltages.

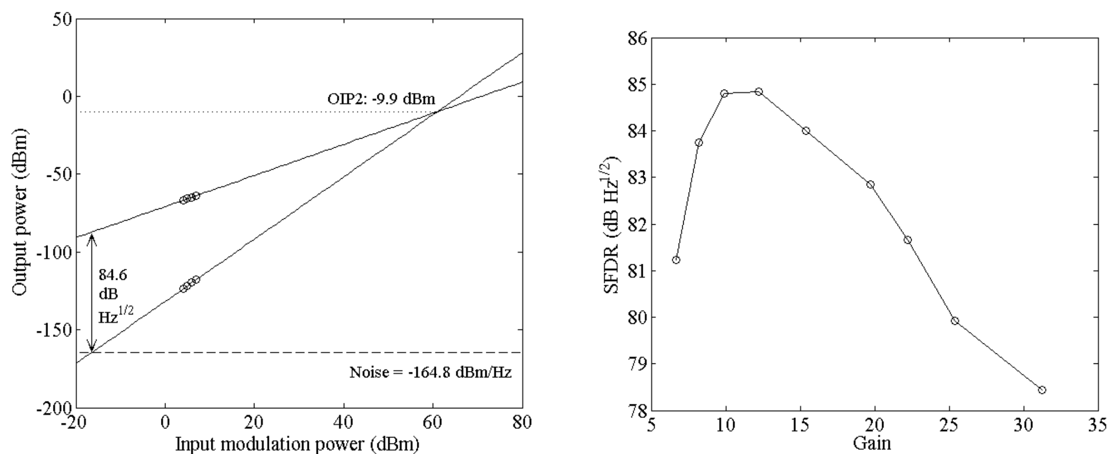

Fig. 3. a) IMD2 measurements at -23 V bias (M = 10.8).

b) Second order dynamic range as a function of gain. Photocurrent ranges from 11 to 70 µA.

Figure 4a) shows the IMD3 measurements at -24 V bias. The photocurrent is 47 µA, the gain is 20.4, the third order intercept point (OIP3) is -19.9 dBm, and the SFDR is 101.5 dB·Hz$^{2/3}$. Figure 4b) shows the SFDR of the APD as a function of gain. Below 24 V of reverse bias, the IMD3s drop below the system noise floor of -150 dBm with a 30 Hz bandwidth.

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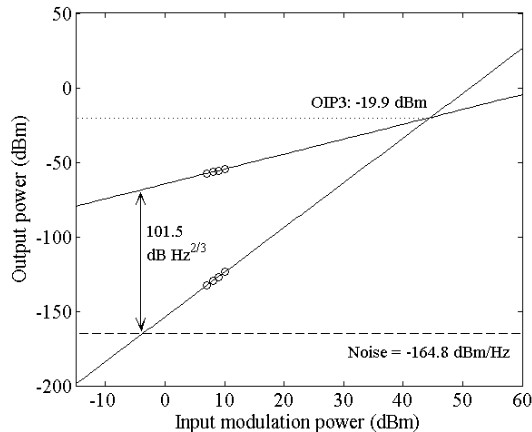
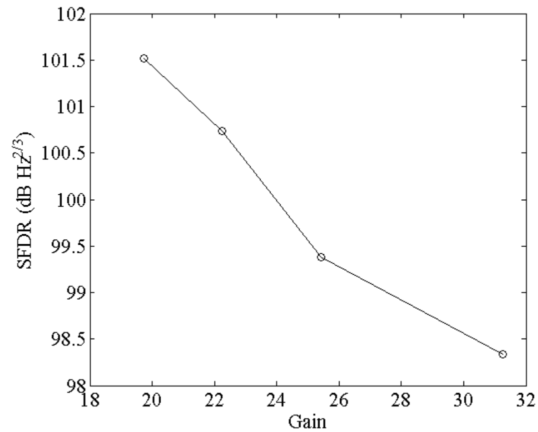


Fig. 4. a) IMD3 measurements at -24 V bias.



b) Third order dynamic range as a function of gain. Photocurrent ranges from 47 to 70 μA.

4. Conclusion

The Ge/Si APD exhibits a high gain-bandwidth product and a low noise factor. Two-tone linearity measurement has shown a good SFDR at microwave frequencies over the operational range of the device. The variations in microwave frequency and DC linearity with changes in gain are shown qualitatively to behave similarly.

Acknowledgements

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References

[1] G.S. Kinsey, J.C. Campbell and A.G. Dentai, "Waveguide avalanche photodiode operating at 1.55um with a gain-bandwidth product of 320 GHz," *IEEE Photon. Tech Lett*. **13**, 842-844 (2001).

[2] A. R. Hawkins, W. Wu, P. Abraham, K. Streubel, and J. E. Bowers, "High gain-bandwidth-product silicon heterointerface photodetector," *Appl. Phys. Lett.* **70**, 303-305 (1996).

[3] Y. Kang, M. Zadka, S. Litski, G. Sarid, M. Morse, M. J. Paniccia, Y.-H. Kuo, J. E. Bowers, A. Beling, H.-D. Liu, D. C. McIntosh, J. Campbell, A. Pauchard, "Epitaxially-grown Ge/Si avalanche photodiodes for 1.3 μm light detection," *Optics Express* **16**, 9365 (2008).

[4] T. Ozeki and E.H. Hara, "Measurement of Nonlinear Distortion in Photodiodes," *Elect. Lett.* **12**, 80-81 (1976).

[5] Y. Kang et al. "Nonlinear Distortions and Excess Noise Behavior of Fused InGaAs/Si Avalanche Photodiode," *Microwave Photonics, 2002. International Topical Meeting on* , pp. 153-156, 5-8 Nov. 2002.

[6] H. Jiang, D.S. Shin, G.L. Li, T.A. Vang, D.C. Scott, and P.K.L. Yu, "The frequency behavior of the third-order intercept point in a waveguide photodiode," *IEEE Photon. Tech. Lett.*, **12**, 540-542 (2000).

[7] T. Kagawa and H. Iwamura, "Effect of the ionization rate ratio on nonlinear distortion in avalanche photodiodes," *IEEE Photon. Technol. Lett.* **8** 417-419 (1996).