Low-voltage Waveguide Ge APD based High Sensitivity 10Gb/s Si Photonic Receiver

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Abstract *We demonstrate low-voltage Ge waveguide avalanche photodetectors (APDs) with gain-bandwidth product over 100GHz. A 5.8dB avalanche sensitivity improvement (1×10^{-12} bit error ratio at 10Gb/s) is obtained for the wire-bonded optical receiver at -5.9V APD bias.*

Introduction

Avalanche photodetectors (APDs) integrated in a silicon photonics platform offer great potential to improve the power budget of Si-based optical interconnects through providing significantly improved optical receiver sensitivity as compared to conventional PIN photodetectors. The key design targets for CMOS compatible Ge APDs are low operation voltage and high sensitivity. In [1], we demonstrated a 10Gb/s Si photonics receiver based on a low-voltage vertical PIN (VPIN) junction Ge waveguide APD wire-bonded to a 40nm LP CMOS trans-impedance amplifier (TIA). A 7dB sensitivity improvement with absolute sensitivity of -22dBm was estimated based on the Q factor extracted from eye diagram measurements. In this paper, a Ge WG APD with a similar design as that in [1] is wire-bonded to a 0.13μm SiGe BiCMOS low-noise TIA [2]. Bit error ratio (BER) measurements were implemented on the wire-bonded optical receiver to directly assess the sensitivity. Also the avalanche noise performance was characterized by excess multiplication noise measurements.

Device Structure & Fabrication Process

The Ge waveguide APDs were fabricated in imec's fully integrated Si Photonics Platform [3]. The cross-sectional dimensions of the Ge APDs are shown in Fig. 1(a). Fig. 1(b) shows a TEM image of the Ge APDs' longitudinal cross section. The spacing between the p-contact plugs is 1.2μm. The simulated doping distribution in the Ge layer is shown in Fig. 1(c). The simple structure of the Ge APDs allows straightforward integration with Si modulators and various passive devices. This heterogeneous Ge/Si VPIN diode configuration results in a strong electric field as high as 1×10^{5} V·cm^{-1} confined in the lower 200nm of the Ge layer at -5.5V bias, as shown in Fig. 1(d), owing to the strong electric field confinement. It is expected that strong avalanche multiplication can take place at moderate applied bias voltage, and that part of the avalanche excess-noise generation can be suppressed [4].

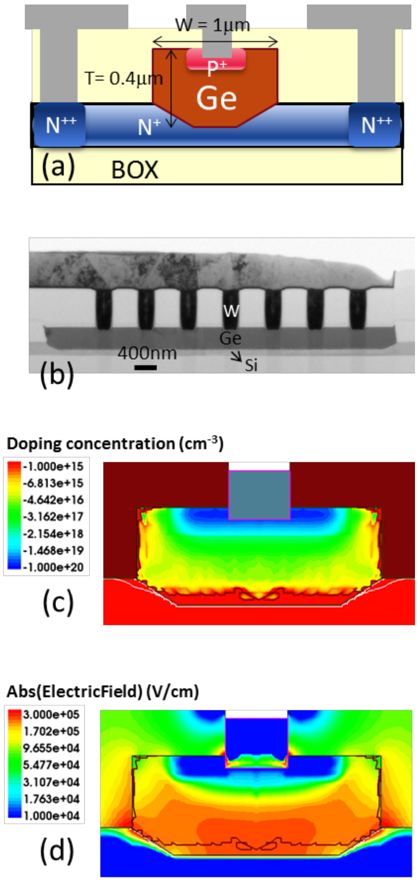


Fig. 1: (a) Schematic cross-section of the Ge waveguide APDs. (b) TEM longitudinal cross-section image. (c) Simulated doping distribution. (d) Simulated electric field distribution at -5.5V.

Standalone APD Characteristics

A static current-voltage characteristic of a 14μm-long VPIN Ge APD device is shown in Fig. 2(a). The device has a low dark current of 17nA at -1V. The light current is measured at 1550nm with an input optical power of -19.6dBm. The measured primary responsivity is 0.6A/W. Both the dark current and the light current increase rapidly as the bias voltage surpasses -5V. The avalanche gain extracted from these static measurements, defined as the multiplication factor of the net-light current (= light current – dark current) is shown in Fig. 2(b). The gain increases sharply as the bias voltage becomes larger than -5V, reaching its maximum value at -6.2V. The avalanche gain is 3.5, 6.3 and 10.0 at 90%, 95% and 98% of the breakdown voltage (defined at -6.2V), respectively.

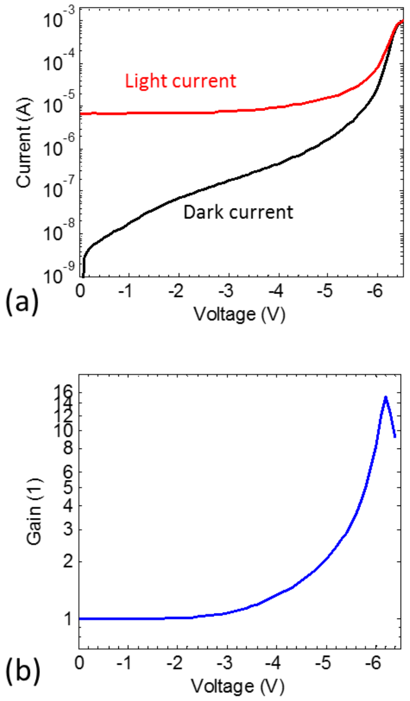


Fig. 2: (a) I-V characteristics of a 14μm-long Ge APD device. (b) Avalanche gain extracted from the static measurements.

Next, small-signal radio-frequency (RF) measurements were carried out. The S_{21} parameter is recorded as a function of frequency for various applied bias voltages at 1550nm, as shown in Fig. 3(a). With increasing bias voltage, the low-frequency RF power increases and the 3dB opto-electrical bandwidth drops substantially. Fig. 3(b) shows avalanche gain extracted from small-signal measurements. As the case in static measurements, the avalanche gain reaches its maximum value at -6.2V. The 3dB bandwidth versus avalanche gain is shown in Fig. 3(c). As the gain exceeds 2, the 3dB bandwidth drops almost inversely proportional to the avalanche gain, due to the avalanche build-up time [5]. At -6.2V APD bias, a 3dB bandwidth of 10.4GHz with avalanche gain of 10.2 is obtained, resulting in a gain×bandwidth product larger than 100GHz.

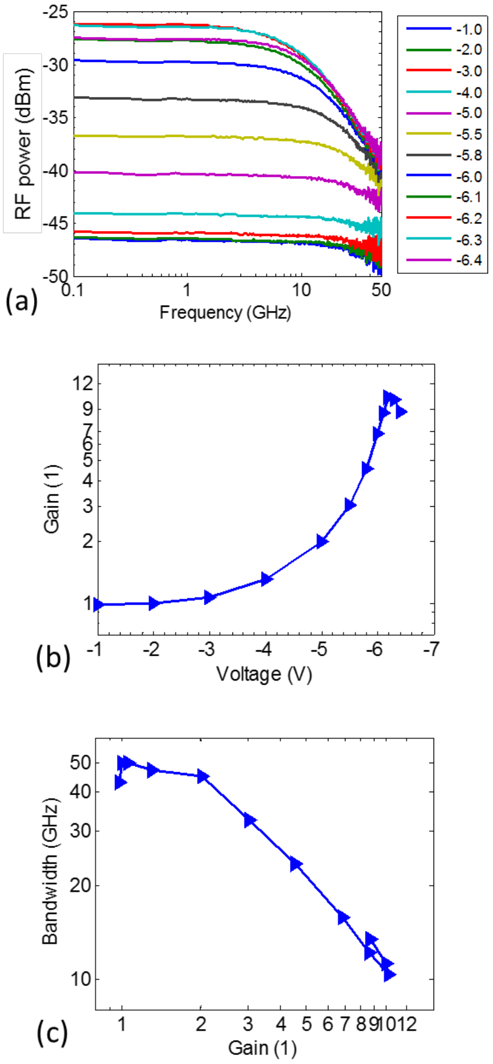
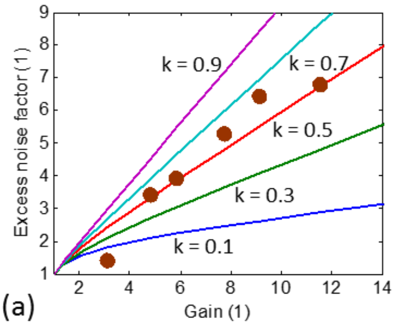
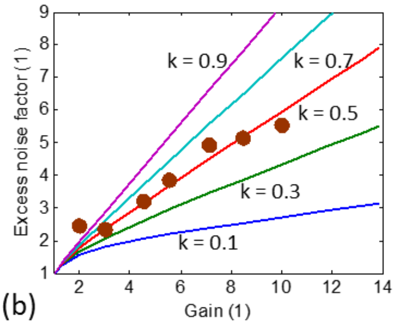


Fig. 3: (a) Small-signal RF measurements of S_{21} parameter for various bias voltages. (b) Avalanche gain extracted from the small-signal measurements. (c) Measured 3dB opto-electrical bandwidth as a function of avalanche gain.

Next, multiplication noise measurements were performed to characterize the avalanche noise performance. The noise current power spectral density (PSD) at 150MHz in both dark current and light current were measured using a low-noise signal analyzer. The excess noise factor *F(M)* as a function of gain is shown in Fig. 4(a) and Fig. 4(b) at 1550nm wavelength for an input optical power of -23.8dBm and -18.8dBm, respectively. Fitting the data for the case of avalanche multiplication in a uniform electric field with electrons initiating the multiplication reveals a k_{eff} (the ratio of holes impact ionization rate to electrons impact ionization rate) of 0.5 in the presented device. This results in a noise current PSD reduction of 35% for an avalanche gain of 10 compared to a bulk Ge APD.



Input optical power, -23.8dBm



Input optical power, -18.8dBm

Fig. 4: Excess noise factor as a function of avalanche gain with an input optical power of (a) -23.8dBm and (b) -18.8dBm, respectively.

APD Receiver Characteristics

The APD device was wire-bonded to a 10Gb/s trans-impedance amplifier (TIA), as shown in Fig. 5(a), to assess the sensitivity. The TIA, implemented in 0.13μm SiGe BiCMOS technology, has a differential output [2]. A 10Gb/s (2^{31}-1) long optical NRZ PRBS data pattern with 8.9dB extinction ratio, as shown in the inset of Fig. 5(b), was launched into the wire-bonded APD receiver. A commercial limiting amplifier (LA) was connected to the TIA. The combination of TIA and LA has an input referred (RMS) noise current of 1.2μA. The LA differential outputs (both the DATA and XDATA port) were fed to a 10Gb/s error detector for BER measurement. The measured differential BER as a function of input optical power for various bias voltages are shown in Fig. 5 (b). The sensitivity increases with increasing bias. At -5.9V APD bias, an absolute sensitivity of -23.4dBm for a 1×10^{-12} BER is obtained, which is 5.8dB higher than the primary sensitivity of -17.6dBm at -1.7V. The avalanche gain, extracted from the small-signal measurements, is about 6 at -5.9V.

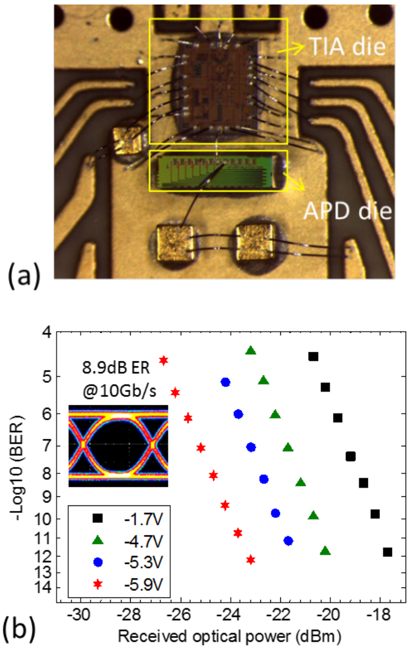


Fig. 5: (a) Optical receiver with a Ge APD device wire-bonded to a TIA. (b) Measured bit error ratio as a function of input optical power for various bias voltages. The inset is the optical reference eye diagram from a commerical modulator.

Conclusions

Low-voltage germanium waveguide APDs are demonstrated with a gain×bandwidth product over 100GHz. The optical receiver based on such a Ge APD demonstrates a 5.8dB sensitivity improvement. This can compensate for certain channel insertion loss of optical data links, and thus help to satisfy the required link power budget.

Acknowledgements

This work was partially sponsored by imec's industry-affiliation program on Optical I/O. We acknowledge the process line in imec for manufacturing the Ge APD devices. We also thank Danny Frederickx and Ludo Viaene for the wire bonding of the Ge APDs to TIAs.

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