A 1310 nm sub-5V Ge APD based optical receiver in a silicon platform for 32 Gbps PAM-4 transmission over 40 km

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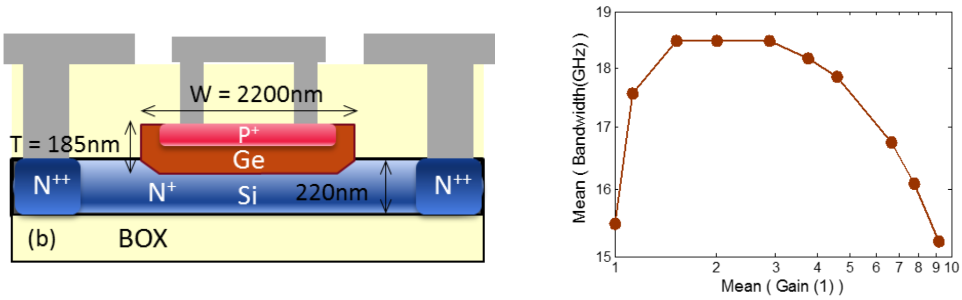
Avalanche photodetectors (APDs) integrated in a silicon photonics platform can significantly improve the link budget of optical interconnects by boosting the optical receiver sensitivity compared to conventional p-i-n photodetectors at CMOS-friendly bias voltages. We demonstrate a silicon-based receiver consisting of a low-voltage (<5V) 1310 nm Ge APD and a low-power BiCMOS transimpedance amplifier. The receiver offers a sensitivity improvement of ~6dB for 32 Gbps PAM-4 transmission over >40 km with a commercially available direct-modulated DFB laser as transmitter, allowing a 4 times higher split ratio in FTTx passive optical networks for the same link budget.

Introduction

Avalanche photodetectors (APDs) can offer a substantial increase in sensitivity compared to p-i-n-photodiodes thanks to the avalanche gain [1-2]. This property is especially useful in power limited optical links such as passive optical networks (PON), where the additional sensitivity can be used to increase the split ratio, allowing the optical line terminal (OLT) to reach more clients for the same transmit power. However, as it inherently takes time to build up the avalanche the bandwidth of such devices is typically limited. Increasing the bit rate with a PAM-4 modulated APD-based link could prove beneficial in terms power and cost, as the bandwidth of the optical and electrical components can remain relaxed whilst maintaining the advantage of a higher power budget due to the APD gain. Germanium APDs on a silicon platform are ideally suited for such applications as their low voltage operation makes them truly CMOS compatible. The photodetector in the proposed optical receiver requires a bias voltage of less than 5V removing the requirement for a dedicated off-chip high-voltage (>15V) generation and connection to the optical transceiver module as is common for conventional III-V based APDs.

Design and characterization

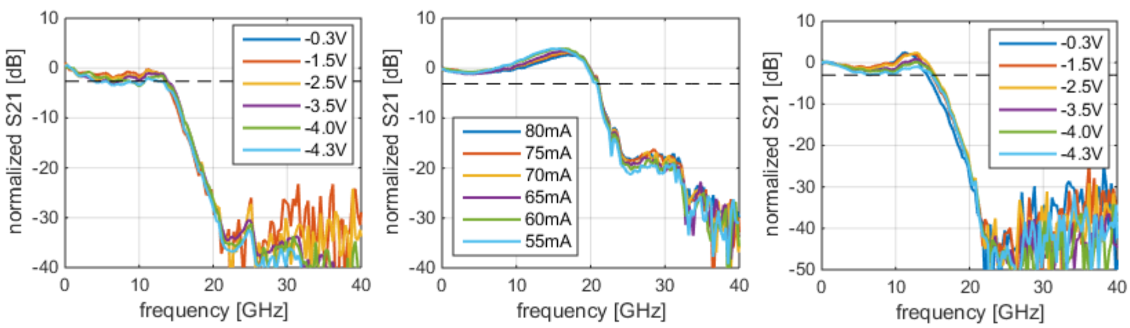
The APD was designed in imec's fully integrated Si Photonics platform as described in [3] and has a primary responsivity of 0.3 A/W around 1310nm. A vertical p-i-n structure is formed by implanting a 220 nm thick single-mode Si waveguide with posphor ions (before Ge growth) and the planarized Ge layer with boron ions as shown in Figure 1.a. A 185 nm thin Ge layer was used to lower the bias voltage of the Ge APD. This results in a wafer-scale mean gain×bandwidth product (GBP) of 140 GHz at -5V bias voltage. Figure 1.b shows the mean 3dB bandwidth versus the mean avalanche gain of this APD structure. Below a gain value of 2 the mean GBP increases due to the widening of the depletion region in the Ge layer. Once the gain passes 4 the bandwidth drops rapidly due to the increased avalanche build-up time.



(a) (b)

Fig.1 (a) cross section of the SiGe APD; (b) wafer-scale measured mean bandwidth vs mean gain of the APD

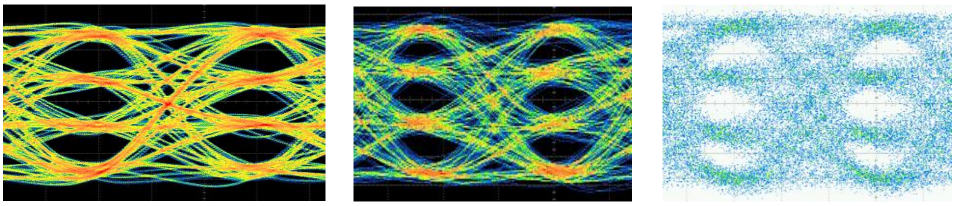
The APD was wirebonded to a transimpedance amplifier (TIA) to evaluate the large signal performance with bit-error rate tests. The TIA is fabricated in a 130 nm SiGe BiCMOS process and was optimized towards linearity and power consumption [4]. Additionally, bandwidth can be traded off for gain by choosing a preferred value of the transimpedance resistance. During the experiments a fixed 133 Ohm transimpedance was found to give the highest gain without limiting the APD bandwidth. Figure 2 shows the frequency responses of the APD+TIA, the DFB and the DFB to APD+TIA link. It's clear that the APD-TIA is the bandwidth-limiting component of the optical link with a bandwidth of 13-14 GHz depending on the bias voltage. The bandwidth of the commercial DFB was measured with a PIN-diode with >34 GHz bandwidth allowing us to neglect its effect on the DFB bandwidth, which is 21 GHz. The frequency response of the laser shows quite some peaking (5-6 dB) between 10 and 20 GHz. An arbitrary waveform generator (AWG) is used to generate an electrical PAM-4 signal to drive the DFB laser. As the focus of the experiment is on the optical receiver, the electrical signal from the AWG is used to flatten the frequency response from the transmitter up to 18 GHz whilst connected back-to-back to a high speed (>34 GHz) PIN-diode. Figure 2 shows an example of the 16 Gbaud electrical eye before and after the frequency response flattening and optical eye diagram from the APD-based receiver. The optical link had a bandwidth of 14 to 15.4 GHz depending on the bias voltage of the APD.



(a) (b) (c)

Fig. 2: (a) small-signal APD-TIA response normalized to the same low frequency gain; (b) small-signal response of the commercial DFB laser; (c) small-signal response of the total link: DFB + APD-TIA

For BER tests the bias current of the DFB was kept constant for all experiments at 70 mA resulting in an optical output power of 8.96 dBm at 1310.2 nm. The laser was operated at room temperature without any temperature control. A 2^{15}-1 long pseudo random symbols stream was generated by the AWG and amplified to ~2.5 Vpp before modulating the laser current. After the fiber channel the polarization is matched that of the on-chip grating couplers used to interface with the Ge APD. The in-fiber power is controlled by a variable optical attenuator (VOA). The grating couplers had an insertion loss of ~6 dB, which in combination with insertion loss of the polarization controller and fiber alignment lead to a fiber-referred primary responsivity of approximately 0.05 A/W in PIN mode. The differential outputs of the TIA were stored on a real-time oscilloscope for offline BER analysis. Due to the limited memory only data streams of ~1 million symbols could be saved in a single data capture, resulting in a minimal BER of just below 1×10^{-6}. A histogram on a fraction of the received signal was used to determine the decision thresholds for demodulation of the complete signal. No equalization or offline post-processing was used.



(a) (b) (c)

Figure 3: Electrical PAM-4 eye from AWG (a) before and (b) after the frequency peaking reduction in the DFB; (c) 32Gbps PAM-4 eyes from the APD-based receiver after 2 km of SSMF fiber.

Results and discussion

First, we determined the an optimal bias voltage to operate the APD+TIA receiver by comparing the optical modulation amplitude (OMA) that was needed to obtain a bit error rate (BER) of 3.8×10^{-3}, i.e. the hard-decision forward error-coding limit or HD-FEC with 7% overhead, for different APD bias voltages. We define the OMA as the power difference between the highest level (P_{11}) and the lowest level (P_{00}) in the PAM-4 eye diagram. One could also use the middle eye as OMA reference by shifting all the BER-curves in figure 4 by -4.8 dB, assuming that the OMA of the middle eye is ~1/3 of the outer eye.

The measurement results in figure 4a clearly illustrate the advantage of operation in avalanche mode of the photodiode: the sensitivity of the receiver improves by roughly 6 dB for a bias of -4.9V compared to -1.2V in PIN-operation. For relatively high input power the BER increases again for the -4.9V bias. This is not the onset of a noise floor, but rather the dynamic range of the TIA that comes into play. If the current input to the TIA becomes too high the amplifier starts to saturate impacting its linearity. This manifests itself in a compression of lower and upper eye (compared to the middle eye in the PAM-4 eye diagram), which in its turn introduces bit errors. A bias of -4.9V was chosen for all further experiments as it demonstrates the lowest OMA while still showing at least 8 dB of dynamic range at FEC-level for Back-to-Back (B2B) transmission.

The same setup was used for transmission experiments with the addition 2, 10, 21 or 42 km of standard single mode fiber (SSMF). Again, a sensitivity improvement of 6 dB is realized in APD operation compared to operation in PIN mode as is indicated in figure 4b. Up to 21 km there no significant difference between the different fiber lengths as we are still operating the link well in its power budget and there is almost negligible chromatic distortion thanks to the near zero dispersion of SSMF in the O-band. At 42 km the power budget did not longer suffice to perform meaningful PIN mode measurements due to a relatively low off-chip responsivity combined with an additional insertion loss of the VOA and fiber connectors of the SSMF, resulting in a maximal in-fiber power of around -6 dBm corresponding to a waveguide-referred OMA of -14 dBm. However, in APD mode error-free reception assuming FEC was possible up to an OMA of -15 dBm, highlighting the benefit of APD-based 32 Gbps optical receiver. In theory the power budget of the optical link (without insertion loss the VOA and connector losses due to the chaining of multiple rolls of fiber) would suffice for 32 Gbps sub-FEC transmission over more than 50 km.

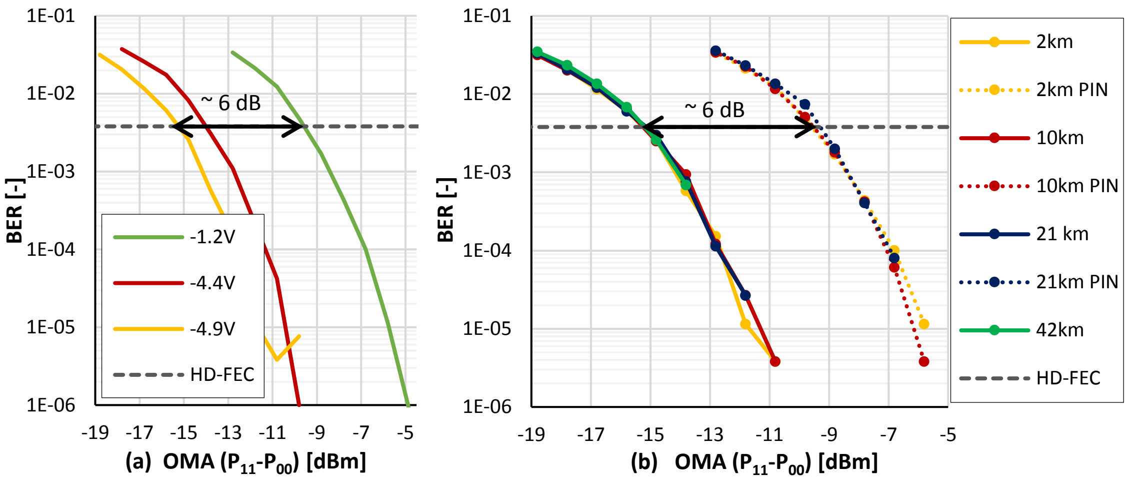


Figure 4: (a) BER as a function of OMA for different APD bias voltages for 32 Gbps PAM-4 in a B2B-transmission. **(b)** BER as a function of OMA for 32 Gbps PAM-4 over 2, 10, 21 and 42 km of SSMF fiber.

Conclusion

We presented a silicon optical receiver consisting of a 1310 nm Ge APD and a linear SiGe transimpedance amplifier. With a bias voltage of only -4.9 V the APD delivers a sensitivity improvement of 6 dB compared to PIN operation enabling transmission over more than 42 km for a 32 Gbps PAM-4 signal or a 4 times higher split ratio in PON networks for the same power budget in 20+ km networks without any optical amplification.

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