25 Gbps low-voltage waveguide Si-Ge avalanche photodiode: supplementary material

ZHIHONG HUANG^{1,*}, CHENG LI¹, DI LIANG¹, KUNZHI YU^{1,2}, CHARLES SANTORI¹, MARCO FIORENTINO¹, WAYNE SORIN¹, SAMUEL PALERMO², AND RAYMOND G. BEAUSOLEIL¹

¹Hewlett Packard Laboratories, 1501 Page Mill Rd., Palo Alto, CA, 94304

²Department of Electrical and Computer Engineering, Texas A&M University, College Station, TX 77843

*Corresponding author: zhihong.huang@hpe.com

Published 21 July 2016

This document provides supplementary information to "25 Gbps low-voltage waveguide Si-Ge avalanche photodiode," <http://dx.doi.org/10.1364/optica.3.000793>. Here we discuss the measurement methods for impulse response, capacitance-voltage, waveguide loss, and analysis for APD receiver sensitivity. © 2016 Optical Society of America

<http://dx.doi.org/10.1364/optica.3.000793.s001>

A. Bandwidth measurement and a APD circuit model

The APD bandwidth was measured using an impulse response method, and the measurement setup is shown in Figure S1a. A femto second laser pulse is coupled to the device, generating electron-hole pairs in germanium to be collected by electrodes. Impulse response from the device is observed from an Keysight DCA86100C sampling scope at time domain. We have fit the impulse response with a RLC circuit model as shown in Figure S1b, with a transfer function of Equation (S1). In the model, we have also introduced a gaussian function besides the transfer function from the RLC circuit which combines the information from carrier transit time and excess RF losses. The product of these two transfer functions produces the blue dashed line, which represents the final fitting of the impulse response. For this particular $4\mu\text{m} \times 10\mu\text{m}$ waveguide APD, we have extrapolated the R, L, C values are 10ohm, 280pH and 32fF, respectively.

$$H(\omega) = H_{\text{gaussian}} \frac{1}{1 - (Q \frac{\omega}{\omega_{rc}})^2 + (j \frac{\omega}{\omega_{rc}})} \quad (\text{S1})$$

where H_{gaussian} is a gaussian transfer function in time domain to compensate external losses, and

$$\omega_0 = \frac{1}{\sqrt{RC}}, \omega_{rc} = \frac{1}{RC}, \text{ and } Q = \frac{\omega_{rc}}{\omega_0} = \frac{1}{R} \sqrt{\frac{L}{C}}$$

B. Capacitance measurement

Capacitance is measured by a Keysight LCR4725 LCR meter with internal voltage source up to 40V. In the setup, the DC probe needles were properly grounded near the tip for femto-Farad capacitance measurement. Capacitances were measured

Fig. S1. **a**, Bandwidth measurement setup by using the impulse response method. **b**, RLC circuit model of a p-i-n photodiode, excluding the transit time response. **c**, Measured impulse response and fitting. The dark green solid line shows the measured data and the blue dashed line shows the product of the two transfer function components considering a gaussian function and a RLC circuit model as shown in Equation (S1).

on various size devices to extrapolate the parasitic capacitances. Figure S2 shows the capacitance density versus bias voltage for an APD and a p-i-n photodiode. Both devices were fabricated on the same wafer with the same layer structure, and the only difference is that the APD has its charge layer boron doped. Near 0V, the APD capacitance is $2\times$ higher than the pin diode since its depletion region expands only to the charge layer. Above 2V, the silicon multiplication and the charge layer are fully depleted and the depletion region starts to penetrate into germanium. The germanium layer is fully depleted and reaches its lowest value around -6V, which determines its AC punch through voltage.

Fig. S2. Capacitance density versus voltage measure for a SiGe APD and a p-i-n diode without charge layer.

C. Waveguide loss measurement

We have measured the waveguide losses by the cut-back method as indicated in Figure S3. We have used single mode fibers to couple both ends of the grating couplers of a silicon waveguide. The peak of the grating coupler mode varies significantly with silicon layer thicknesses and the grating coupler on this wafer has the least transmission loss near 1620nm. Figure S3 shows the coupling loss of -15 to -16dB at 1550nm. The extrapolated loss values are shown in the table embedded.

D. Receiver sensitivity analysis

The APD sensitivity can be written as Equation (S2) [1]:

$$P_{\text{sen}}|_{\text{APD}} = \frac{1}{R} \left\{ Q \left[\frac{\langle i_{n,TIA}^2 \rangle_c}{\langle M \rangle^2} + 2q \langle M^2 \rangle I_{dm} B I_2 \right]^{1/2} + q Q^2 F(M) I_1 B + i_{\text{offset}} \right\} \quad (\text{S2})$$

where the APD responsivity and noise figure $F(M)$ is defined by:

$$R = \left(\frac{hc}{q\lambda \times QE} \right) \quad (\text{S3})$$

$$F(M) = kM + \left(2 - \frac{1}{M} \right) (1 - k) \quad (\text{S4})$$

M is the multiplication gain, k is the ratio of impact ionization coefficient between electrons and holes. Lower k value results in a lower noise figure, better frequency response, and better sensitivity of the APD. $\langle i_{n,TIA} \rangle_c$ is the TIA's equivalent input

Wavelength	WG loss (dB/cm)	Coupling loss (dB)/side
1550nm	12.9	16
1580nm	11	13
1620nm	10	8.2

Fig. S3. Waveguide loss measurement by using cutback methods. The extrapolated coupling loss and waveguide loss are shown in the table below.

noise current and it is $2\mu\text{A}$ for our CMOS receiver. i_{offset} comes from the TIA circuit current introduced by mismatches of following stages which is independent of Q , and it is calibrated to be $30\mu\text{A}$. I_{dm} is the APD primary dark current at unity gain. B is the operating data rate. Q is the quality factor determined by B and the bit error rate (e.g., for 10Gb/s and a BER of 10^{12} , $Q = 7$). QE is the quantum efficiency of the photodiode. $F(M)$ is the APD excess noise factor defined above. $\langle M \rangle$ is the average excessive gain, and $\langle M^2 \rangle = F(M) \langle M \rangle^2$.

REFERENCES

1. R. Smith and S. Personick, "Receiver design for optical fiber communication systems," in "Semiconductor devices for optical communication," (Springer, 1982), pp. 89–160.