Supplemental Document

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Supplement DOI: https://doi.org/10.6084/m9.figshare.12446102

Parent Article DOI: https://doi.org/10.1364/OPTICA.393537

Supplementary Material

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Published 9 July 2020

This document provides supplementary information to the research article entitled "40 Gbps heterostructure germanium avalanche photo receiver on a silicon chip," https://doi.org/10.1364/OPTICA.393537.

1. FABRICATION

P-i-n waveguide photodetectors with lateral silicon-germanium-silicon (Si-Ge-Si) heterojunctions were fabricated in CEA-LETI's cleanroom facilities on a fully integrated nanophotonic platform using 200 mm silicon-on-insulator (SOI) wafers and standard complementary metal-oxide-semiconductor tools and processes. The SOI substrates consisted in 0.22 µm thick silicon (Si) layers on top of 2 µm thick buried oxide (BOX) layers. At first, passive nanophotonic components and devices, such as interconnecting waveguides and fiber-to-chip surface grating couplers, were fabricated with 193 nm deep-ultraviolet (deep-UV) optical lithography and dry etching. Afterwards, thermal oxidation of about ~0.01 µm was used to have a silicon dioxide (SiO_2) cap layer prior to ion implantation. *p*-type and *n*-type Si regions were obtained by boron (B) and phosphorous (P) ion implantation. The concentration of dopants in *p*-type and *n*-type regions were in excess of 10^{19} at/cm^3, the same as used for p++ and n++ contacts in Si-based optical modulators. An 0.80 µm thick oxide cladding was deposited on top prior to cavity patterning. The oxide cladding was completely etched down to the Si surface, followed by Si layer patterning and deep-rib waveguide etching to form cavities with ~0.06 µm Si floors just above the BOX. A more than a 1µm thick Ge layer was selectively grown inside those cavities with germane (GeH_4). After the 450°C growth of a Ge seed, the temperature was ramped up to 750°C and the remainder of the Ge layer grown in a reduced pressure-chemical vapor deposition (RP-CVD) chamber, followed by a 1-hour-long H_2 annealing at 750°C to heal defects. A chemical mechanical polishing (CMP) process was used to reduce the Ge thickness down to ~0.26 µm and recover a flat surface. A few micrometers thick oxide cladding was then deposited for Ge passivation and insulation. 0.40 µm × 0.40 µm vias were sub-sequently patterned and etched down to the Si doped regions. Ni-based silicidation was then conducted to improve contact access resistance. At the end, Ti/TiN/W stacks were used as metal plugs. Electrodes consisted of a patterned AlCu layer.

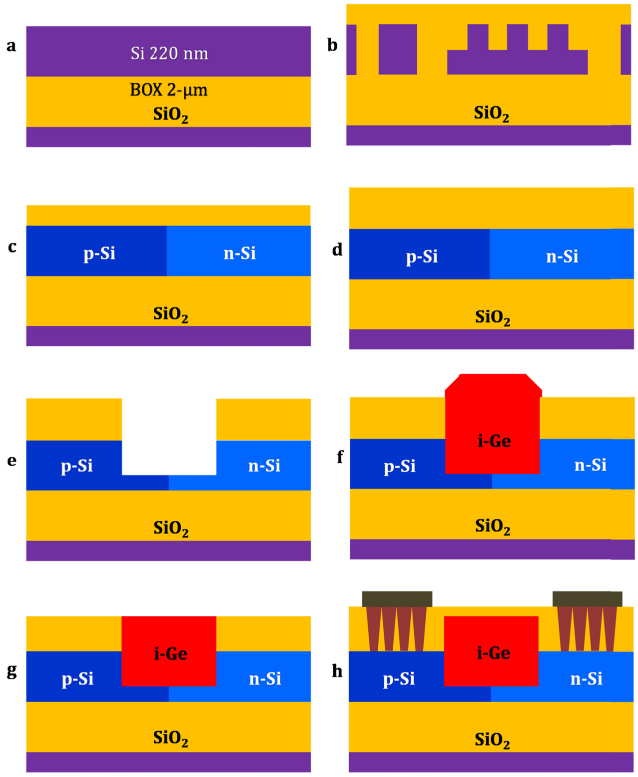

Fig. S1. Schematics of the fabrication process of p-i-n photodetectors with lateral silicon-germanium-silicon hetero-junctions.

2. DEVICE CHARACTERIZATIONS

Current-voltage measurements

Conventional static current-voltage tests were performed under dark and light-illuminated conditions. The light coming from a tunable laser source was coupled into the silicon chip through a standard single-mode optical fiber (SMF-28) using focusing surface grating couplers. The surface grating couplers were optimized for quasi-transverse electric (TE) polarization and a central wavelength of 1.55 μm. The grating couplers were connected to a short single-mode strip waveguide, having a 0.22 μm × 0.5 μm (thickness × width) cross-sectional area, launching a light into the Si-Ge-Si photodetector thanks to a butt-coupling scheme. Photodetectors were biased using an electrical probe connected to a Keithley Source Measurement Unit. Based on these tests, both device responsivity and avalanche gain were determined, as defined in the main text.

Small-signal radio-frequency measurements

Small-signal radio-frequency measurements were carried out to assess the opto-electrical bandwidth properties of the hetero-structured photodetectors. Experiments were performed with a conventional radio-frequency test set-up and a Lightwave Component Analyzer (LCA), with an internally built-in laser and modulator. The launching of the modulated optical signal into the silicon chip occurred via surface grating coupler, as explained earlier. The Si-Ge-Si photodetectors were reversely biased with the help of bias-tee and Keithley Source Measurement Unit. Prior to testing, calibrations of the radio-frequency path were implemented to take into account the contributions from cables and probes. The small-signal radio-frequency experiments were performed by collecting the response of the S_{21} transmission parameter in the LCA as a function of frequency ranging from 0.1 GHz to 50 GHz.

Large-signal data link measurements

The high-speed operation of the Si-Ge-Si photodetectors was studied through large-signal measurements. These experiments consisted of eye-diagram acquisitions and input power sensitivity assessments with a bit-error-rate (BER) testing. Data were transmitted in a non-return-to-zero (NRZ) format with an on-off keying (OOK) modulation. The pseudo-random-binary-sequence (PRBS) pattern of length $2^7 - 1$ was used for transmission bit rates of 32 Gbps and 40 Gbps, respectively. The data rate limit of the pattern generator was 40 Gbps. Tests beyond this bit rate were thus not performed. The distributed feedback laser emitting at a wavelength of 1.55 μm was modulated with an external modulator, followed by an optical amplification with an erbium-doped fiber amplifier (EDFA), an optical filter to lower the spontaneous emission noise and a fibered coupler. One output of the coupler was attached to the 60 GHz photodiode of an oscilloscope to display the modulated input signal as a reference. The other output of the coupler was transmitted into the device via an optical attenuator and an in-line optical power meter to control the power level. The input light polarization was controlled to maximize the transmission of the quasi-TE waveguide mode and optimize the signal intensity. The modulated optical signal was launched from the optical fiber into the silicon chip thanks to a focusing surface grating coupler, followed by on-chip detection in the Si-Ge-Si photodetector. Detection was performed without the use of an integrated trans-impedance amplifier or limiting amplifiers. Electrical data were collected through the RF test set-up by applying the reverse bias to the photodetector with the use of a RF probe connected to a bias-tee. Data were directly sent from the RF bias-tee output to a high-speed sampling oscilloscope, giving re-constructed eye diagrams at desired data rate. BER assessments were performed by inserting an external 38 GHz broadband electrical amplifier between the RF bias-tee output and the BER detection module. The minimum level requirement was 100 mV peak-to-peak signal voltage to have credible BER measurements.

3. APD SENSITIVITY ESTIMATION

The sensitivity of our silicon-germanium-silicon avalanche photodetector can be estimated using the theoretical framework adapted from Ref. [1]. Receiver sensitivity corresponds to the minimal power, for which optical signal can be detected for a specified BER threshold and this can be calculated from the signal quality factor Q, conventionally defined as:

$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0} \tag{S1}$$

where I_1 and I_0 are signal amplitudes for "*1*" and "*0*" and σ_1 and σ_0 are respective root-mean-square (RMS) noise variances at bits "*1*" and "*0*", respectively. In addition, we assume that the "*0*" bits do not carry the optical power, and thus $P_0 = I_0 = 0$. The optical power is only carried for "1" bits, yielding (for a signal amplitude under an avalanche multiplication gain):

$$I_1 = 2GRP_r \tag{S2}$$

where, P_r is the minimum optical power for the receiver, i.e. photo-receiver sensitivity we target to estimate.

The RMS noise variances σ_1 and σ_0 can be expressed as follows:

$$\begin{aligned} \sigma_1^2 &= \sigma_s^2 + \sigma_d^2 + \sigma_t^2 \\ \sigma_0^2 &= \sigma_d^2 + \sigma_t^2 \end{aligned} \tag{S3}$$

where σ_s is the signal level noise variance, σ_d is the dark-current noise variance and σ_t corresponds to the thermal noise variance, respectively. they are expressed in following way:

$$\begin{aligned} \sigma_s^2 &= 2q\left(G^2\right)F(2RP_r)\Delta f \\ \sigma_d^2 &= 2q\left(G^2\right)FI_d\Delta f \\ \sigma_t^2 &= \left(\frac{4k_BT}{R_L}\right)F_n\Delta f \end{aligned} \tag{S4}$$

Here, q is the electron charge (q = 1.60217662e^{-19} C), F is the avalanche excess noise factor (F = ~0.25), Δf is the photo-receiver bandwidth for a non-return-to-zero bit stream ($\Delta f = BR/2$, where BR is the transmission bit rate, here 40 Gbps), G is the avalanche multiplication gain, R is the reference device photo-responsivity (R = 0.49A/W), I_d is the dark-current (I_d = 1 µA; 10 µA; and 100 µA), k_B is the Boltzmann constant (k_B = 1.38064852e^{-23} m^{2}kgs^{-2}K^{-1}), T is the temperature (T = 293 K), R_L is the load resistance (R_L = 50 Ω), and F_n is the noise figure of the photo-receiver amplifier (F_n = 2).

Combing Equations S1 - S4, we can express the Q factor as follows:

$$Q = \frac{2GRP_r}{\sqrt{\left(\begin{aligned} &2q\left(G^2\right)F(2RP_r)\Delta f + \\ &2q\left(G^2\right)FI_d\Delta f + \\ &\left(\frac{4k_BT}{R_L}\right)F_n\Delta f \end{aligned}\right)} + \sqrt{\left(\begin{aligned} &2q\left(G^2\right)FI_d\Delta f + \\ &\left(\frac{4k_BT}{R_L}\right)F_n\Delta f \end{aligned}\right)}} \tag{S5}$$

In order to achieve a desired BER of 10^{-9}, the Q parameter equals 6. Solving the Equation S5 for minimum optical power P_r, we can estimate the optical power sensitivity of an avalanche photo-receiver.

The estimated sensitivity of an hetero-structured silicon-germanium-silicon receiver as a function of an avalanche multiplication gain is shown in Fig. S2 for different dark-current levels of 1 µA, 10 µA, and 100 µA.

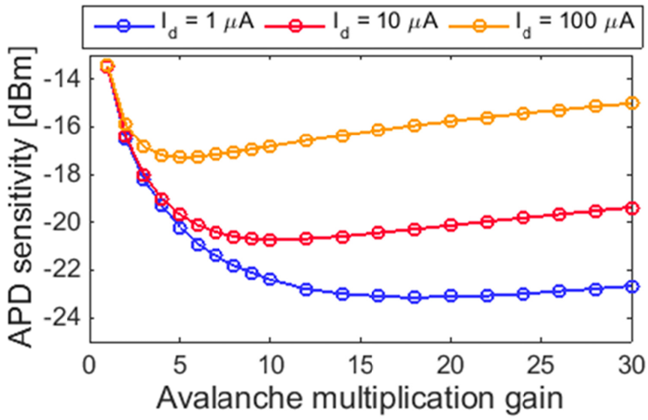

Fig. S2. Estimated sensitivity of an avalanche photo-receiver with hetero-structured silicon-germanium-silicon photodiode for different levels of dark-current. .

References

1. G. P. Agrawal, Fiber-Optics Telecommunication Systems Third Edition (Wiley-Interscience, 2002)