Recent advances in Ge/Si PIN and APD photodetectors

John E. Bowers*1, Anand Ramaswamy1, Daoxin Dai1, Wissem Sfar Zaoui1, Yimin Kang**,2, Tao Yin2, and Mike Morse2

1 ECE Department, University of California, CA 93106 Santa Barbara, USA
2 Intel Corporation, 2200 Mission College Blvd, CA 95054 Santa Clara, USA

Received 3 September 2009, revised 26 December 2009, accepted 29 December 2009
Published online 21 June 2010

Keywords Ge/Si, photodetectors, p-i-n junctions, design, performance

* Corresponding author: e-mail bowers@ece.ucsb.edu, Phone: +1 805 893 8447, Fax: +1 805 893 7990
** e-mail yimin.kang@intel.com

Photodetectors on a Si platform are important because of the opportunity to manufacture literally millions of photodetectors per wafer and because the use of a mature CMOS (Complementary Metal-Oxide-Semiconductor) process results in low cost and high uniformity. In this paper, we review recent results on Ge-Si-based PIN-type photodetectors and avalanche photodetectors (APD). We show several exciting advantages of SiGe photodetectors namely, the higher thermal conductivity of Si and Ge, resulting in higher power capability, and the lower k factor, resulting in higher gain bandwidth products in APDs.

1 Introduction

Photodetectors play an important role in optic communications, optical sensing, and optical imaging. Photodetectors on a Si platform are important because of the opportunity to manufacture literally millions of photodetectors per wafer and because the use of a mature CMOS (Complementary Metal-Oxide-Semiconductor) process results in low cost and high uniformity. Silicon is transparent in the infrared regime (1310nm~1550nm) and an effective approach is to combine Si with InGaAs [1] or Ge [2, 3]. Ge is attractive for scaling to 300 mm wafers. There are dislocations due to the lattice mismatch between Ge and Si, but it is possible to minimize their impact with careful processing and device design [2]. There are several exciting advances in SiGe photodetectors that utilize the inherent advantages of this system, namely, the higher thermal conductivity of Si and Ge, resulting in higher power capability, and the lower k factor, resulting in higher gain bandwidth products in APDs [2]. In this paper, we review recent results on Ge-Si-based PIN-type photodetectors and avalanche photodetectors (APD).

2 High power Ge-Si n-i-p detectors

The dynamic range of microwave links increases with received shot-noise limited optical power [3]. This necessitates the development of photodiodes that have high optical power handling capability. We analyze the two factors that limit the high current operation in a PIN photodetector, i.e., thermal effects and space charge effects [4]. Ge is 16x more thermally conductive than InGaAs, which is traditionally used in these detectors, and Si is 30x more thermally conductive than the InGaAsP waveguide layers in those detectors [5-7] hence, improved thermal performance should be possible in a waveguide SiGe PIN photodetector (Fig. 1). Our measurement results show that a 7.4 μm × 500 μm device was able to dissipate 1 W of electrical power. The 3 dB bandwidth (4.38 GHz) of the device remains fairly constant even at operation with 50 mA photocurrent, which makes it attractive for RF photonic applications. 2D thermal simulations show the improved thermal performance in transporting the heat laterally and also indicates the impact of the SiO2 layer in blocking heat flowing into the substrate.

2.1 Device structure

The Ge waveguide detector is grown on top of a Si rib waveguide by a selective epitaxial process. The detector in this work has a width of 7.4 μm and a length of 500 μm. The final thickness of the Ge layer is 0.8 μm. The thicknesses of the p+ silicon and buried oxide layer are 1.5 μm and 1.0 μm, respectively. The layout...
of the photodetector and a schematic of the cross section are shown in Figs. 1(a) and 1(b).

As the light propagates along the Si waveguide it evanescently couples upwards into the Ge region where it is absorbed. Details of the growth and fabrication process can be found in [1]. Figure 2 shows a SEM cross-section of the completed device.

**Figure 1** (a) Schematic of Ge detector integrated with passive Si waveguide, (b) Cross-section schematic of device.

2.2 DC characteristics Figure 3 shows the saturation characteristics of the device at an input wavelength of 1550 nm for different reverse bias values. The x-axis takes into account a coupling loss of 4 dB. It can be seen that at a lower bias the output current saturates faster because of carrier screening effects [7]. A maximum photocurrent of 125 mA under 8 V of reverse bias was observed. This corresponds to 1 W of electrical power dissipation in the device. Thermal simulations of the device show that most of the heat is generated in the absorber region (i-Ge). This heat travels downwards into the p doped Si region and then spreads laterally. The presence of the buried oxide (BOX) layer prevents the heat from being dissipated via the substrate and causes the temperature to build up in the device. The max temperature (in the absorber) is 85 °C when 1 W of power is being dissipated across it.

**Figure 3** Photocurrent dependence on input power for different bias voltages.

2.3 Microwave characteristics We explore the potential of these devices for microwave applications by measuring their linearity and radio frequency (RF) response under small signal and large signal modulation. Figure 4(a) shows the frequency response of the device at different photocurrent levels.

**Figure 4** (a) Frequency response of 7.4 μm x 500 μm device at different photocurrent levels for a fixed reverse bias (5 V). (b) 3 dB bandwidth as a function of photocurrent.
It is known that the bandwidth of photodiodes decreases at high input optical power levels. However, Fig. 4(b) shows that up to 50 mA of photocurrent and under 5V reverse bias, the 3 dB bandwidth of the device remains fairly constant at ~4.38 GHz.

For high dynamic range microwave photonic applications, photodiodes need to have high linearity. Typically, what this means is that the cubic (third order) non-linear coefficient in the photodiode needs to be minimized. This is so because in narrow band systems it is the third order distortion components that fall very close to the carrier signals and hence cannot be filtered out. A common metric used to characterize 3rd intermodulation distortion (IMD3) is the 3rd order Output Intercept Point (OIP3). It is obtained graphically by plotting the output power versus the input power on a logarithmic scale. When the power in the fundamental frequency increases by 1dB, the power in the IMD3 increases by 3dB. By extending the two curves with slopes 1 and 3 respectively, the intercept point (IP3) is obtained. The higher the OIP3 the more linear the device. We used a standard two-tone and more complicated threethree-tone technique for the linearity measurement. We looked at the linearity of the Si-Ge n-i-p detectors both as a function of bias voltage and as a function of photocurrent at a frequency of 1 GHz. Figure 5 shows the OIP3 results from both measurement techniques, wherein theoretically, the three-tone OIP3 should be 3 dB less than the two-tone OIP3 [5]. Also, the OIP2 was measured. It can be seen that with increasing bias the OIP3 increases and reaches a maximum of 36.49 dBm at 8 V.

Figure 5 OIP3 and OIP2 at 1 GHz and 40 mA of photocurrent

The large signal characteristics of these detectors were also evaluated. It was found that the maximum RF power that could be extracted from these devices was 14.35 dBm at 1 GHz. Although this is relatively low in comparison to some InP detectors, the devices have tremendous potential because of their superior power dissipation capability. Detectors that can handle large amounts of RF power open up the possibility of using them as high-power RF output stages [9]. Current efforts are focused on impedance matching for efficient power transfer and also improving the device design to realize better heat transfer out of the active area.

3 High performance Ge-Si APD
3.1 APD with an ultra-high GBP

Since silicon has a low k-value (<0.1), which makes it one of the most promising candidates for APDs that have both high gain and high bandwidth simultaneously. It is a good way to combine the low-k value of Si and the high absorption of Ge to have an excellent CMOS-compatible APD by using the structure of a separate-absorption-charge-multiplication (SACM). Figure 6 shows the schematic configuration for a normal-incident type Si/Ge APD [2], which consists of a Si multiplication layer, a Si charge layer, and a Ge absorption layer. The thicknesses and the doping concentrations for all layers are shown in the inset. The charge layer is very thin and has the correct doping so that one obtains sufficient gain via a high electric field in the Si multiplication layer while the electric field in the Ge-absorber is low. A silicon-nitride film was deposited and serves as an anti-reflection coating in the 1310 nm window to improve the quantum efficiency.

Figure 6 (a) Schematic configuration of the Ge/Si SACM APD device; (b) the parameters for the layers.

Figure 7 The dark current and total current on a 30 μm-diameter Ge/Si SACM APD versus bias voltage under an optical power of -20 dBm at 1310 nm.
Figure 7 shows the measured I-V curve for a 30 μm-diameter Ge/Si SACM APD when the illuminated optical power $P = -20$ dBm at the wavelength of 1310 nm. The dark current is also shown in Fig. 7. One sees the breakdown voltage is around $-26$ V. Figure 8 shows the measured gain curves at different optical powers. The measured gain is determined by normalizing the responsivity of the APD to the primary responsivity of a p-i-n device fabricated on the same wafer. The primary responsivity is 0.55A/W at 1310 nm and the correspondent external quantum efficiency is 52.2%.

Figure 8: The measured gain curves versus bias voltage under $-20$ dBm, $-26$ dBm and $-30$ dBm at 1310 nm.

Figure 9(a) shows the frequency responses measured with a lightwave component analyzer under $-20$ dBm input power at bias voltage values between $-24$ V and $-28$ V. We can clearly see that the response part at low frequencies follows a similar behavior to the DC-gain curve from Fig. 8. On the other hand, the part corresponding to high frequencies keeps increasing, which is similar to results reported in [11-13]. Therefore, the origin of the reported electrical 3 dB-bandwidth (BW) enhancement is not only due to the enhancement at high frequencies, but also due to the decrease of the response at low frequencies. Figure 9(b) shows the simulated frequency responses, which agree well with the measurements.

Figure 9(b) shows the simulated frequency responses, which agree well with the measurements.

Figure 10 shows the voltage dependence of the bandwidth. It can be seen that the BW decreases between $-23$ V and $-26$ V and then increases again due to the frequency response enhancement exceeding 10 GHz. At around $-23$ V, the multiplication gain is low and consequently the APD is RC and transit time limited. As the voltage increases to $-26$ V and the gain reaches its maximum, the avalanche buildup time increases, which becomes the limitation for the BW. Thus the BW drops. As the voltage increases above $-26$ V, the gain drops and thus the multiplication time, giving a raise to the BW. However, the BW in this enhanced mode is higher than the transit time limited BW at lower voltages. This can be explained by investigating the internal properties such as the electron and hole drift velocities across the Ge absorption layer.

In Figure 10, we also show the impact of optical power on the BW. Around $-23$ V, there is no considerable influence, and the BW value is almost constant. As the bias voltage increases, any perturbation of the electric field through excess charge carriers has a big influence on the gain and on the speed performance of the APD. This behavior is in general due to the trade-off between the gain and the BW. High optical powers produce low gains and high BWs, and vice versa.

Figure 11 shows the extracted GBP of the APD under different input powers. The GBP is proportional to the gain increase at low gain values due to the constant BW. As the gain increases, the BW drops due to the multiplication time, and the GBP saturates [10]. Beyond the gain peak, the GBP starts to increase again dramatically because of the...
BW enhancement and the slow decrease of the gain. The highest measured GBP is 868 GHz at –30 dBm, corresponding to a gain of 65.3 and a BW of 13.3GHz [14, 15]. The increase in GBP at higher voltages can be explained partially by the rise of hole velocity in the absorber layer and space charge effects. The experimental observation of shorter impulse response at higher voltages strongly supports this explanation.

![Figure 10](image1.png)

**Figure 10** The measured electrical BW versus bias voltage under –20 dBm, –26 dBm and –30 dBm at 1310 nm.

![Figure 11](image2.png)

**Figure 11** Experimental GBP versus gain for input optical powers of –20 dBm, –26 dBm and –30 dBm at 1310 nm.

### 3.2 The impedance of the Si/Ge APD and the equivalent circuit

In order to understand the peak enhancement of the frequency responses shown in Fig. 9, we examined the APD impedance by measuring the microwave reflection parameter $S_{22}$ as the bias voltage is varied (see Figs. 12(a) and 12(b)). One sees that the real part $Z_r$ and the imaginary part $Z_i$ of the impedance are strongly voltage-dependent. At relatively high voltage (e.g., $|V| > 25.4$ V), the real part $Z_r$ of the APD impedance has a peak at a certain frequency $f_r$. The imaginary part $Z_i$ of the APD impedance has a transition from a positive to a negative value at almost the same position $f_r$. This is what usually occurs when there is a resonance. In the avalanche region, the impact ionization avalanche will introduce a delay between the AC current and the electric field (i.e., the AC voltage). With a small signal model, this delay due to the impact ionization avalanche in the Si multiplication layer is equivalent to an inductance. Therefore, an equivalent circuit model with an LC-circuit for the avalanche region as shown in Fig. 13 [16]. The carrier transit-time effect is also included in this model by using an additional RC circuit (the left part in Fig. 13), which is coupled to the right part through a current-controlled current source.

![Figure 12](image3.png)

**(a)**

**Figure 12** (a) The measured impedance; (b) the measured Smith chart.
Figure 13 The equivalent circuit of the SACM APD.

All the parameters for the elements included in the equivalent circuit were extracted by fitting the measured $S_{22}$ with a genetic-algorithm (GA) optimization. In Figs. 14 (a)-(b), the measured (dotted curves) and fitted (solid curves) $S_{22}$ parameters show a very good agreement. From the equivalent circuit with the extracted parameters, we calculate APD frequency response as shown in Fig. 15. One sees that the simulated curve (solid) and measured data (circled) agree well with each other [16], especially the peak-enhancement at the high frequency.

Figure 14 The measured and fitted reflection coefficients for (a) $V_{\text{bias}} = -26.6$ V; (b) $V_{\text{bias}} = -26.2$ V.

Figure 15 The measured and fitted frequency responses for $V_{\text{bias}} = -26.2$ V and $V_{\text{bias}} = -26.6$ V.

4 Conclusions PIN detectors using Ge absorbers on Si substrates may find widespread applications for digital and analog systems due to the high power capability, high efficiency, low dark current, and the fact that they can be manufactured on 300 mm substrates in a standard CMOS fab. SiGe APD detectors may allow for the first time, application of highly sensitive receivers at 40 and 100 Gbit/s. The resonant behaviour of the frequency response and impedance are an interesting result of the inductance and negative resistance resulting from impact ionization in the gain region.

Acknowledgements This work was sponsored by the Defense Advanced Research Projects Agency (DARPA) under contract number HR0011-06-3-0009.

References