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HP Laboratories
HPL-2015-28

Keyword(s):

APD; low voltage

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External Posting Date: April 6, 2015 [Fulltext] Approved for External Publication
Internal Posting Date: April 6, 2015 [Fulltext]

Low-voltage Si-Ge avalanche photodiode

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***Abstract*—Here we report a Si-Ge avalanche photodiode (APD) with a breakdown voltage of only -10V. The highest measured bandwidth is 15.8GHz for a 20μm diameter device. A bandwidth of 13.2 GHz at gain of 22.2 is obtained for the same device, giving a 290GHz gain-bandwidth product at 1550nm wavelength.**

I. Introduction

With the increasing demand of big data in computing and storage, on-chip optical interconnect has become an uprising trend for datacenter and high performance computers. Large integrated silicon photonics is appealing to this application due to its low cost and compatibility with Si CMOS processes, as well as its benefit of dramatically increased data transfer rate and reduced cross talk and power consumption. A tranceiver's power consumption is largely determined by the sensitivity of its optical system, in which a Ge p-i-n photodiode is often used due to its low operation voltage despite avalanche photodiodes provide better sensitivities. Although Ge-only APDs have been recently reported to operate at voltages below 10V [1]–[3], they often suffer from the low gain-bandwidth product (GBP) (low bandwidth at high gain) due to the near-unity impact ionization coefficient ratio of germanium - conventionally a none-ideal material for APDs. On the other hand, Si-Ge avalanche photodiodes, which uses silicon as the avalanche multiplication region, has consistently reported over 300GHz gain-bandwidth product and 10dB better sensitivity than p-i-n receivers [4], [5]. Recently, a Si-Ge APD with breakdown voltages below 12V and bandwidth of 10GHz was reported [6], and this was achieved by reducing the silicon multiplication region to 100nm in a separate absorption-charge-multiplication structure. Here in our work, we report a Si-Ge avalanche photodiode using a thin silicon multiplication region. A 20μm-diameter device has a breakdown voltage of -10V and the highest bandwidth of 15.8GHz at gain of 5.5. Gain-bandwidth product of 290GHz is achieved at bandwidth 13.2GHz and gain of 22.2 for the same device when operated at -9.98V bias.

The APD structure is shown in Fig. 1. We have used a normal incident design by top illuminating laser light to a circular mesa with various diameters. The devices were built on a 220nm-thick SOI substrate with 3μm-thick buried oxide. The 220nm Si was first implanted with Arsenic to form a n^+ conductive layer followed by a selective growth of 150nm-thick intrinsic silicon on its device region. Boron was then implanted on the mesa at 5keV energy to form a charge layer. SIMS result indicates boron distributes within the top 50nm of the regrown-Si, leaving the rest of the Si as an intrinsic multiplication region. 400nm germanium was subsequently selectively grown followed by a boron p^+ implant throughout germanium. Finally the wafer was passivated by SiO_2 and opened hole for Al contacts.

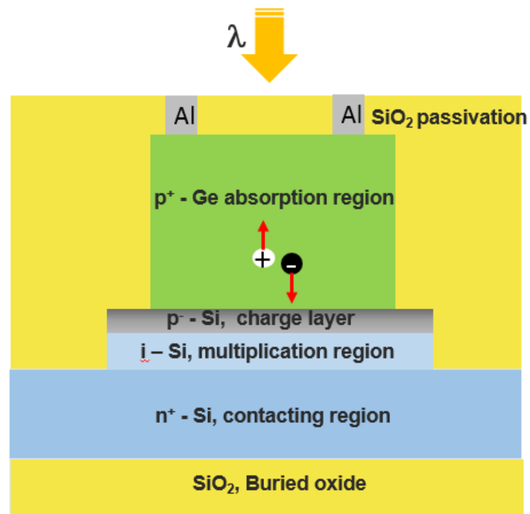

Fig. 1. Schematic of the normal incident Si-Ge avalanche photodiode.

Fig. 2 show current-voltage (IV) characteristics of a 20μm-diameter APD. IV was measured with a keithley 2400 source meter and photocurrent was measured at 1550nm. In our measurement, we cannot detect current below 1nA due to the setup noise, making the current of this device undetectable below -5V. But currents near DC punch-through and breakdown voltage can be clearly obtained. The DC punch through voltage is determined to be -6V after comparing its reponsivity with a device without charge layer; it can also be determined by a minor hump of the IV on some devices.

Fig. 3 shows a frequency response of the same 20μm-diameter normal incident APD operating at -8.2V. The bandwidth is measured using an impulse method: 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 Agilent DCA86100 sampling scope at time domain. In this method, APD acts as a low frequency pass filter to the incoming light pulse and broadens its electrical impulse response. The inset of Fig. 3 shows the electrical impulse response of the APD and it has a full-width-half-maxium (FWHM) of 30ps. The

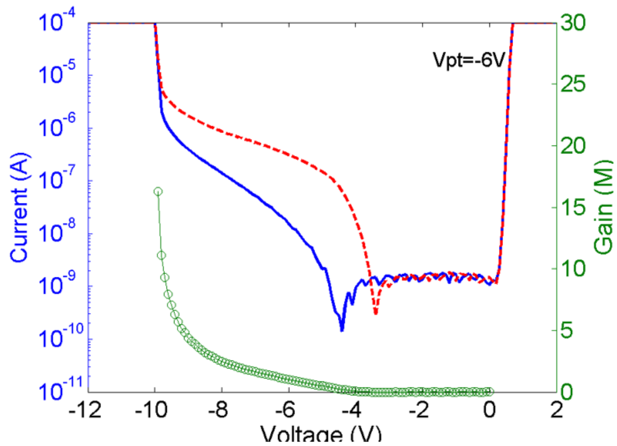

Fig. 2. APD curent-voltage and gain-voltage characteristics for a 20μm-diameter normal incident Si-Ge APD. Its shows breakdown voltage at -10V

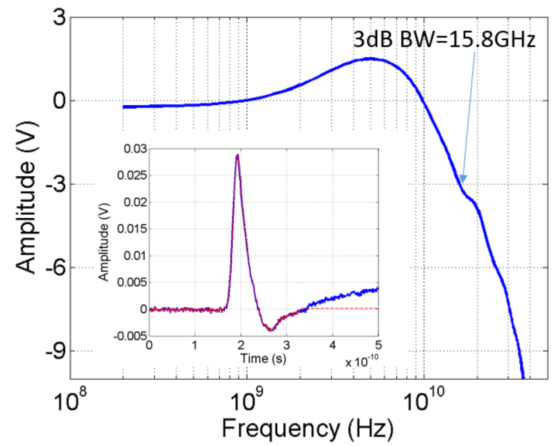

Fig. 3. Extrapolated BW at 8.2V for the 20μm-diameter normal incident Si-Ge APD, and the 3dB bandwidth is 15.8GHz at gain of 5.5. The inset shows the impulse response of the APD with a FWHM of 30ps.

time domain results can be transformed to frequency domain through fourier transform as shown in Fig. 3. By using this method, 3dB bandwidth of this device is 15.8GHz at -8.2V voltage, corresponding to a gain of 5.5.

Fig. 4 shows the 3dB bandwidth versus gain for the same device. Multiplication gain is determined by comparing the impulse response amplitude at each bias to the one at unity gain. This method provides slightly different results from the ones obtained from IV characterization, but it is more accurate to reflect the actual gain at RF frequencies. All gain results reported in this paper is determined by this method. The highest measured bandwidth for this device is 15.8GHz at gain of 5.5. As we increase the DC bias of the device, its bandwidth drops slowly due to carrier multiplication, but still maintains around 15GHz up till -9.6V at gain of 15 - thank to the low impact ionization ratio of silicon. As the bias continues to increase, the device bandwidth drops slightly faster and we have obtained a bandwidth of 13.2GHz at gain of 22.2, making the highest gain-bandwidth product of 290GHz for this device. This value is in the same range of the reported Si-Ge APDs by using Si multiplication region [4], [5]. And it is significantly better than the Ge-only APDs.

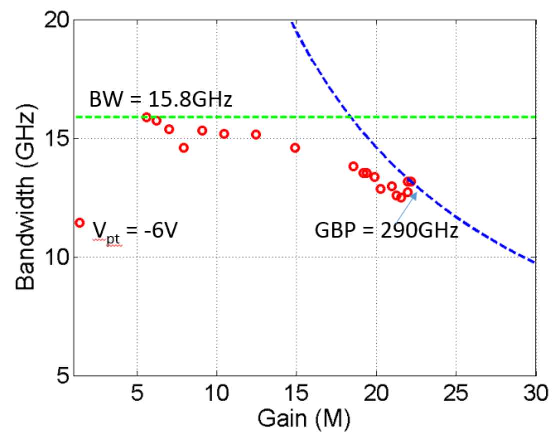

Fig. 4. Bandwidth versus gain for the the 20μm-diameter normal incident Si-Ge APD. The blue dash line shows a constant gain-bandwidth product of 290GHz; the green line show s a constant bandwidth of 15.8GHz.

II. Conclusion

We report a Si-Ge avalanche photodiode with Si multiplication region. By reducing its Si multiplication region to 150nm, we successfully reduced its breakdown voltage to -10V, as well as achieving a 15.8GHz bandwidth and 290GHz gain-bandwidth product for a 20μm-diameter normal incident device.

Acknowledgment

The devices are fabricated at Institute of Microelectronics (IME), Singapore. The authors would like to thank Ning Duan, Lianxi Jia (Larry) and Chee-Wei Tok for device fabrication. The authors would also like to thank Jason Pelc and Wayne Sorin for their helpful discussions in device measurements.

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