

Si avalanche photodetectors fabricated in standard complementary metal-oxide-semiconductor process

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The authors report silicon avalanche photodetectors (APDs) fabricated with 0.18 μm standard complementary metal-oxide-semiconductor (CMOS) process without any process modification or a special substrate. When the bias is above the avalanche breakdown voltage, CMOS-compatible APD (CMOS-APD) exhibits negative photoconductance in photocurrent-voltage relationship and rf peaking in the photodetection frequency response. The reflection coefficient measurement of CMOS-APD indicates that rf peaking is due to resonance caused by appearance of inductive components in avalanche region. The rf-peaking frequency increases with the increasing reverse bias voltage. © 2007 American Institute of Physics. [DOI: 10.1063/1.2722028]

Silicon photodetectors fabricated by the complementary metal-oxide-semiconductor (CMOS) process are very promising for short-distance optical access networks and optical interconnect applications.^{1,2} Using CMOS technology, a low-cost monolithic optical receiver having a photodetector as well as other necessary electronic circuits such as amplifiers and clock and data recovery circuits can be realized. Furthermore, with readily available low-cost 850 nm AlGaAs/GaAs vertical-cavity surface-emitting lasers, CMOS optical receivers can provide cost-effective solutions for many optical link applications.^{1,2}

For realization of high-responsivity and high-speed photodetectors compatible with CMOS technology, avalanche photodetector (APD) can be attractive because it can provide internal gain. Yang *et al.* presented a silicon APD optical receiver using silicon-on-insulator technology and achieved 10 Gbits/s with gain larger than 8.³ In addition, InGaAs/InAlAs APD results show that the avalanche process can enhance the gain-bandwidth product with the help of the internal rf-gain effect in avalanche region.⁴

In this letter, we present Si avalanche photodetectors fabricated with the standard CMOS technology without any process modification or special substrates. Furthermore, we experimentally observe negative photoconductance in photocurrent-voltage relationship and rf peaking in photodetection frequency response for CMOS-compatible avalanche photodetectors (CMOS-APDs). In order to provide explanations for rf peaking, we investigate the impedance characteristics by measuring reflection coefficients of the device and show that the rf peaking is associated with resonance caused by inductive components appearing in the avalanche region.

Figure 1 shows the cross-sectional diagram of CMOS-APD fabricated by 0.18 μm standard CMOS process for our investigation. Using the standard CMOS process, two types of p - n junctions can be implemented; one p +/ n -well junction and the other n -well/ p -substrate junction. We use only the vertical p +/ n -well junction in order to eliminate the slow diffusion currents in the substrate region that limit high-speed operation. In addition, multifinger electrodes with

0.5 μm finger spacing are formed so that photogenerated carriers do not go through the lateral diffusion path. The vertical p - n junction photodetector structure can also mitigate the edge breakdown in the avalanche regime. The active area of our CMOS-APD is about $30 \times 30 \mu\text{m}^2$. The optical window is formed by blocking the salicide process during the fabrication.

For characterization of fabricated CMOS-APD, 850 nm light from a laser diode was modulated by an electro-optic modulator and then illuminated on CMOS-APD through a lensed fiber. Figure 2 shows current-voltage characteristics with and without optical illumination. CMOS-APD has low dark currents and the avalanche breakdown voltage (V_{BK}) is 10.2 V. Figure 3 shows avalanche gain as well as photocurrents. The photocurrent is determined by subtracting dark currents from CMOS-APD photodetected currents, and avalanche gain is defined as the ratio of photocurrents between a given bias voltage and 1 V.

As can be observed in Fig. 3, the photocurrent increases with the increasing reverse bias voltage (V_R) until it reaches the maximum value at V_{BK} . When V_R is larger than V_{BK} , the photocurrent starts to decrease and CMOS-APD exhibits negative photoconductance in its photocurrent-voltage characteristics. Similar negative photoconductance has been observed in InGaAs/InAlAs APD.⁴ The negative photoconductance characteristics in CMOS-APD can be explained by

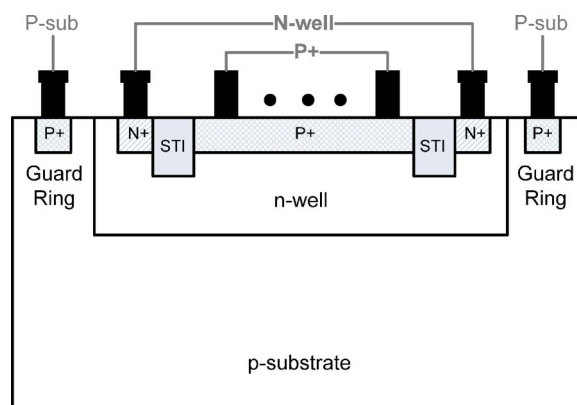


FIG. 1. Schematic cross section of fabricated avalanche photodetector.

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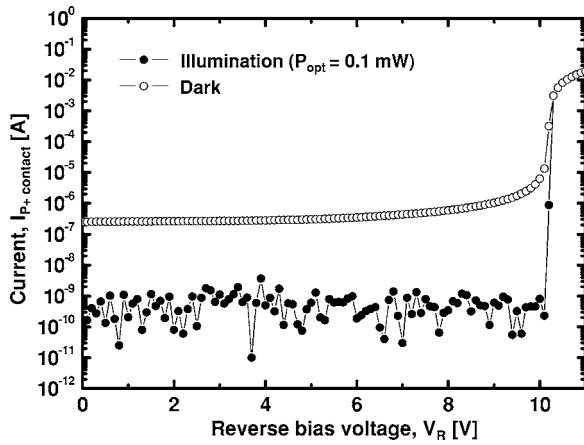


FIG. 2. Current-voltage characteristics of the APD under dark and illumination conditions. The incident optical power is 0.1 mW.

space charge effect and thermal heating. When the device is well into avalanche breakdown, current density becomes very high, and, consequently, carrier space charges are generated and junction temperature increases.⁵ As a result, avalanche gain decreases. These can be also observed when the incident optical signal power is sufficiently high thus increased current density.⁵ The inset of Fig. 3 shows avalanche gain as a function of incident optical power at V_R of 10.0 and 10.2 V. At $V_R=10.0$ V, avalanche gain is constant with respect to incident optical power, whereas, at V_R of 10.2 V, avalanche gain decreases with increasing optical power.

Figure 4 shows the optical modulation frequency response of CMOS-APD at different bias voltages when the incident optical power is 0.2 mW. Interestingly, at V_R larger than V_{BK} , rf peaking is observed at the high frequency region. Such rf peaking has been also reported in InGaAs/InAlAs APD.⁴ The rf peaking can be explained by changes in the impedance characteristics of CMOS-APD in avalanche region. As in transit-time diodes such as impact ionization avalanche transit-time (IMPATT) diodes,⁵ the impedance of CMOS-APD can have an inductive component at V_R above V_{BK} in avalanche region and this inductive component can cause rf peaking.

To investigate the impedance characteristics of CMOS-APD, we measured electrical reflection coefficients of the

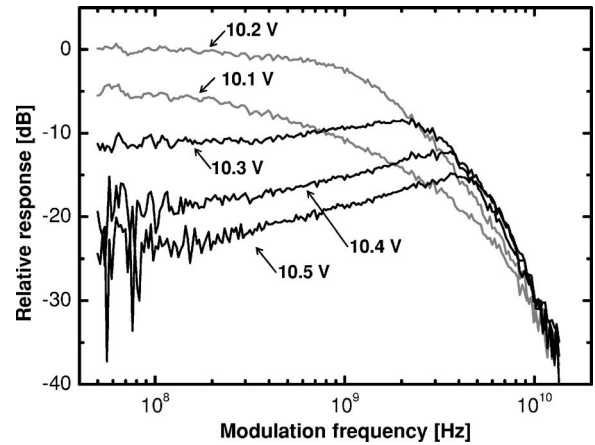


FIG. 4. Optical modulation frequency response at different bias voltages when the incident optical power is 0.2 mW.

device from 50 MHz to 13.5 GHz using vector network analyzer with on-wafer calibration without any optical illumination. Figure 5 shows measured reflection coefficients at different bias voltages on Smith chart. At V_R of 10.0 V, CMOS-APD does not have any inductive components. However, at V_R larger than V_{BK} , the device reactance changes from capacitive to inductive and then again to capacitive as the frequency increases. From this impedance characteristic on Smith chart, it is believed that CMOS-APD has inductive component as well as capacitive component in avalanche regime. We can expect that these inductive and capacitive components can cause resonance which results in rf peaking in photodetection frequency response.

Under optical illumination condition, the impedance characteristics are not changed significantly due to the small amount of current change provided by optical illumination compared with the device dark current in avalanche regime.

In Fig. 4, it is noted that the rf-peak frequency increases with increasing V_R . This can be explained by the fact that the inductance in avalanche region is inversely proportional to the current⁵ and the CMOS-APD current increases as V_R increases, as shown in Fig. 2.

In summary, Si APD devices were fabricated in standard CMOS process and characterized. The device exhibits negative photoconductance in photocurrent-voltage relationship

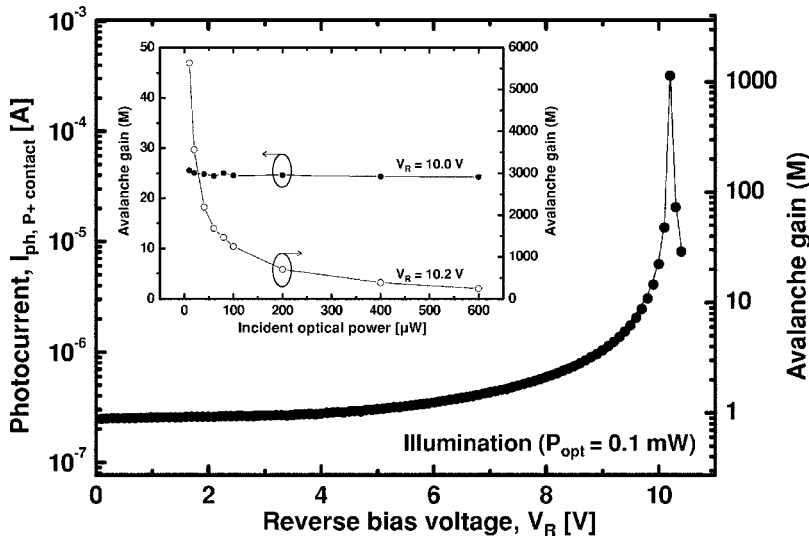


FIG. 3. Photocurrent and avalanche gain as a function of applied reverse voltage when 0.1 mW optical signal is illuminated to the device. The inset is avalanche gain as a function of incident optical power at V_R of 10.0 and 10.2 V.

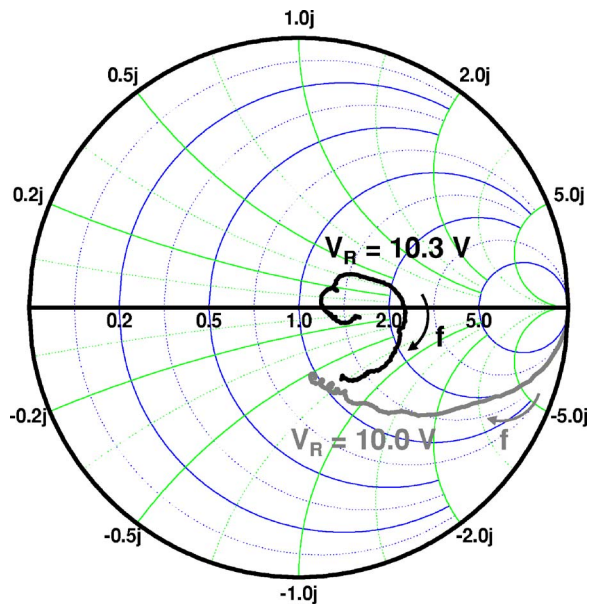


FIG. 5. Reflection coefficient of the CMOS-APD at V_R of 10.0 and 10.3 V. S parameter is measured from 50 MHz to 13.5 GHz.

and rf peaking in photodetection frequency response at the bias voltage above the avalanche breakdown voltage. The impedance characteristics of CMOS-APD indicate that rf peaking is due to resonance caused by the appearance of inductive components in avalanche region.

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