Reliability considerations of high speed Germanium waveguide photodetectors

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ABSTRACT

A 30 Gb/s Ge waveguide photodetector was demonstrated and its reliability under elevated temperatures and high stress biases were investigated. For different reverse biases, the slopes of the dark current increment versus stress bias time curves were initatively found to be the same and made the lifetime extrapolation feasible. The lifetime of the Ge waveguide photodetector under different stress bias was predicted by using a simple extrapolation method. To maintain the ten-year lifetime of the Ge waveguide photodetector, the bias voltage should be kept lower than -3V. For the first time, the degradation mechanism under stress biases was analyzed in detail by the reaction-diffusion model. The experimental results agree well to the theoretical derivation based on reaction-diffusion model.

Keywords: Germanium waveguide photodetector, Reliability, Silicon photonics

1. INTRODUCTION

Owing to its low-cost manufacturing, seamless on-chip integration with electronics by using the complementary metal oxide semiconductor (CMOS) technology, silicon photonics has been identified as a most promising candidate for future generation optical interconnects and communication systems\(^1\). One of the key components needed to build the integrated silicon photonic systems is the Germanium (Ge) waveguide photodetector. In the past years, many high speed and high responsivity Ge waveguide photodetectors have been reported and some figure of merits can be comparable to the commercialized photodetectors\(^2\)-\(^5\). Considering their practical applications in the optical communication systems, Ge waveguide photodetectors should have not only superior technical performances, but also high reliability. Due to the performance degradation with aging time, the reliability of Ge waveguide photodetectors should be proven.

Up to now, many researches on the reliability of III- V photodetectors have been reported. It is usual to accelerate the aging of them to obtain the required reliability and the degradation mechanisms within a reasonably short period\(^6\). In order to estimate the lifetime of the photodetectors, hundreds or thousands of devices will perform the accelerated life tests at elevated temperatures and under constant high bias voltage. During the accelerated aging test, the main observed parameter change is a substantial increase of the dark current. And the dark currents of each device are monitored \emph{in situ} throughout the test\(^7\). By applying the Arrhenius’ equation, the activation energy of the relevant failure mechanism can be extracted and the lifetime of the photodetectors can be predicted\(^8\). However, it usually takes thousands of hours to finish these tests\(^9\). On the other hand, the accelerating aging factor can also be the stress bias. As is known to people, the 3dB bandwidth and the responsivity of the photodetectors increase with the reverse bias. But it would affect the reliability of the photodetector if higher bias voltage was applied onto it for a long time. So it is not appropriate to increase the bias voltage in order to gain higher bandwidth or other merits. To the best of our knowledge, there is little knowledge concerning the degradation behavior of Ge waveguide photodetectors under high stress biases, and the degradation mechanism has not been well studied yet.

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In this paper, we designed and fabricated a compact Ge waveguide photodetector. The photodetector exhibited a 3dB bandwidth of 22GHz and a clear open eye diagram at 30 Gb/s. The reliability of the photodetector under elevated temperatures and stress biases were also evaluated. The lifetime of the photodetector under different reverse bias was extrapolated by using a simple method. In order to maintain the ten-year lifetime of the Ge waveguide photodetector, the moderate bias voltage should be kept lower than -3V. The dark current degradation mechanism was also explained in detail based on the reaction-diffusion model which is often used to characterize the negative bias temperature instability (NBTI) effects in MOSFETs.

2. DEVICE DESIGN AND FABRICATION

The reported Ge waveguide photodetector is illustrated in Fig. 1(a). The Ge absorption layer is integrated on the top of a rib waveguide on a SOI substrate, and it’s a vertical PIN structure. The light in the rib waveguide can be evanescently coupled to the upper Ge layer. Simulation results by using the beam propagation method show that nearly 95% of the light is absorbed when the Ge length reaches about 8μm. The device was fabricated on a SOI substrate with 220nm thick top silicon. The rib waveguide has a width of 600nm and a slab thickness of 60nm, which can confined the mode well in the waveguide. It was tapered to Ge width of 1.6μm to improve the coupling efficiency. Firstly the wafer was lightly doped to get the p type region and then heavily doped to obtain good ohmic contacts. Prior to Ge epitaxy, a rapid thermal annealing (RTA) process at 1030°C for 5 seconds was performed to activate the dopants. Then the Ge layer was selectively grown by using the two step growth approach. The thickness of the Ge layer was intended to be 500nm. Subsequently, the N++ implantation was undertaken to form the n type region and good ohmic contacts and the dopants in Ge were activated by another RTA process at 500°C for 5 minutes. Then about 1μm upper cladding oxide was deposited for surface passivation. Finally, the TaN/Al Ground-Signal-Ground electrodes were formed. The optical micrograph of the fabricated Ge waveguide photodetector and the input silicon waveguide is shown in Fig. 1(b).

3. EXPERIMENTAL RESULTS

3.1 High speed performance

The 3dB bandwidth of the Ge waveguide photodetector was measured to be 22GHz at -3.5V bias by using the Agilent PNA Network Analyzer. In order to verify the viability of the reported photodetector in the optical communication system, the 30Gb/s data transmission measurement was undertaken by using the Tektronix digital sampling oscilloscope (DSA). The measurement setup was shown in Fig. 2. The polarization of the light generated in the tunable laser was controlled by using a polarization controller (PC). The commercial 40Gb/s modulator was driven by a 2^31-1 pseudo-random binary sequence (PRBS) generated by the pulse pattern generator (PPG) after the amplification of the 20GHz driver. The modulated light was coupled to the reversely biased device under test (DUT) (Ge PD) and the output electrical signal was extracted by a 50Ω high speed GSG probe. After the amplification of a 26.5GHz transimpedance amplifier (TIA) and a limiting amplifier (LA), the corresponding signal was fed into the DSA. Both the PPG and the DSA were synchronized to the same clock. The optical eye diagram at the output of the commercial modulator and the electrical eye diagram at the Ge photodetector output are shown in Fig. 2. Although the optical eye diagram of the modulator was not very good which showed much noise, the output electrical eye diagram could open clearly and the
signal to noise ratio (SNR) was about 11dB. With better impedance matching, we believed that higher speed and better quality eye diagrams of the Ge waveguide photodetector would be achieved.

**Fig. 2.** Schematic of the eye diagram measurement setup and the measured optical and electrical eye diagrams.

### 3.2 Reliability characterization

For the devices involving a heterogeneous interface with lattice mismatch, the reliability of Ge photodetectors is always a concern from the practical application perspective. To evaluate its long-term performance, the reliability of the reported photodetector was investigated under elevated temperatures and stress biases. The dark current at -1V was selected as the representative target to be monitored.

Firstly, measurements at four elevated temperatures of 25°C, 50°C, 75°C, 100°C were performed for the reported photodetector. As is shown in Fig. 3(a), the dark current at -1V bias increases from 0.59μA to 1.1μA and on average it increases by a factor of 0.2 every 10°C. To gain additional insight into the dark current mechanism, the activation energy was extracted by using the data from Fig. 3(b) and according to the following equation:

\[
I_{dark} = BT^{3/2} e^{-E_a/kT} (e^{qV_a/2kT} - 1)
\]

where B is the proportionality coefficient, T is the temperature, E_a is the activation energy, κ is the Boltzmann constant and V_a is the bias voltage. The Arrhenius plot of the dark current is shown in Fig. 3(c). Due to the Shockley-Read-Hall (SRH) process, the activation energy of the trap assisted tunneling was figured out to be ~0.155eV at -0.2V bias and ~0.017eV at -1.5V bias, respectively. Considering these activation energies, it can be deduced that the dark current at lower reverse bias might originate from the bulk material since the activation energy is larger. While with the increase of the bias, the activation energy decreased in the same temperature range, which indicated that the dark current would increase more easily at higher reverse bias. This also confirmed that the high bias voltage might be an important factor leading to the device failure.
To evaluate the performance degradation of photodetector under high stress bias, accelerated aging tests were undertaken at high stress biases while the temperature was maintained at room temperature. Firstly, the I-V curve with the voltage in the range of -1.5V to 0V was swept without the application of stress bias. Then the dark current at -1V was extracted and can be used as the fresh dark current.

The another I-V curve sweep was performed after the stress bias time $t_{s}$, as shown in Fig. 4(a). In this way, the dark currents at -1V after different stress bias time can be extracted. Compared with the fresh dark current, the characteristics of the relative magnitude of the dark current changes with stress bias time can be shown in Fig. 4(b). It can be seen that the slopes of the three curves are the same (around 0.18), which indicates that the degradation mechanism under different stress biases is the same. Following the same mechanism, the lifetime of the photodetector under low bias can be obtained by extrapolation\textsuperscript{10}. The specific extrapolation steps are as follows.

Fig. 4. (a) Illustration of the measurement sequence of the accelerated aging tests at high stress bias. (b) The relative magnitude of the dark current under different stress biases.
The device failure was defined as the state in which the gain of the dark current was 10. Then the lifetime at each stress bias can be extracted and the lifetime extrapolation curve is shown in Fig. 5. This plot provides a quantitative method to evaluate the device lifetime as a function of the reverse bias. The ten-year lifetime breakdown voltage was estimated to be -3V, which means that the moderate bias voltage should not exceed -3V in order to maintain the ten-year operation time. From the fitted line in Fig. 5, we can deduce that the photodetector can work effectively for about 4500 hours at -3.5V bias at room temperature. This indicates that the photodetector has high reliability and it is very promising to be used in the 30Gb/s receiving systems.

Fig. 5. The lifetime extrapolation curve. The red dashed line stands for the ten year lifetime.

The slope of the dark current increase with the stress time is interestingly found to be similar with that of the negative bias temperature instability (NBTI) effects in MOSFETs. Therefore, the physical mechanism leading to the degradation can be further discussed as follows based on reaction-diffusion model, which is often used to characterize the NBTI effects. When the Ge layer is grown on the Si substrate, dangling bonds of Si and Ge will be generated due to the lattice constant mismatch. These dangling bonds are electronic states and can be occupied by the electrons if not passivated. Since precursor gases composed of disilane (Si₂H₆) and germane (GeH₄) were employed for the epitaxial growth of SiGe and Ge layers, the dangling bonds of Si and Ge may be occupied by the H atoms. As a result, Si-H and Ge-H bonds especially the former will be generated, as shown in Fig. 6. When the high stress biases were applied, the Si-H and Ge-H bonds would be broken by a thermal chemical reaction. The released hydrogen would diffuse away from the interface due to the density gradient, which will be explained later. Thus, the dangling bonds were generated again which would result in the interface traps. Since these interface traps are electronic states and can be randomly occupied by the electrons, they would become carriers recombination centers, thus increase the dark current and cause the performance degradation.

Fig. 6. Schematic illustration of the reaction-diffusion model applied in the Ge waveguide photodetector.
The whole process can be divided into two phases, which includes the reaction phase and diffusion phase. In the reaction phase, the rate of the interface traps generation can be given by:

$$\frac{dN_{it}}{dt} = k_F (N_0 - N_{it}) - k_R N_H(0) N_{it}$$  \hspace{1cm} (2)$$

where $N_{it}$ is the interface state density at a certain time $t$, $N_0$ is the initial density of Si-H bond, $k_F$ is the forward dissociation rate constant, $k_R$ is the reverse annealing rate constant and $N_H(0)$ is the H concentration at the interface. The released hydrogen would diffuse away from the interface. In the diffusion phase, the rate of the interface traps generation is related with the concentration of hydrogen diffusing away, which is described by:

$$\frac{dN_{it}}{dt} = D_H \frac{d^2 N_H}{dx^2} + N_H \mu_H E_{ox} + \frac{\delta}{2} \frac{dN_{it}}{dt}$$  \hspace{1cm} (3)$$

where $D_H$ is the diffusion constant and $\mu_H$ is the drift mobility.

Combing Eq. (2) and Eq. (3), the interface states density can be obtained as follows:

$$N_{it} = A t^n$$  \hspace{1cm} (4)$$

so

$$I \propto J_{gen} \propto N_{it} = A t^n$$  \hspace{1cm} (5)$$

$$\ln(\frac{\Delta I}{I_{fresh}}) \propto \ln N_{it} = n \ln t + \ln A$$  \hspace{1cm} (6)$$

If the diffused hydrogen is in the form of both H and H$_2$, the slope $n$ is in the range of 1/6–1/4. And the slopes of the three curves in Fig. 5 fit well in this range. Therefore, the degradation mechanism can be well explained by the RD model. In order to improve the reliability of the Ge waveguide photodetector, measures should be taken to avoid the formation of Si-H and Ge-H bonds and to improve the quality of the Si-Ge interface.

4. CONCLUSION

In summary, a high speed Ge waveguide photodetector was demonstrated and its reliability was investigated. By using an extrapolation method, the lifetime of the photodetector under different reverse bias was predicted. In order to maintain the ten-year lifetime of the reported Ge waveguide photodetector, the bias voltage should be kept lower than -3V. The degradation mechanism under stress biases was analyzed in detail based on reaction-diffusion model for the first time. This work paves the way for future research on the reliability of Ge waveguide photodetectors and effective measures should be taken to improve their reliability.

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REFERENCES


