Degradation mechanisms and lifetime assessment of Ge Vertical PIN photodetectors

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Abstract: Dark current degradation mechanisms in Ge VPIN photodetectors were studied. A methodology to estimate the failure percentages has been developed and applied. Degradation/recovery processes and E_a-decrease of I_{dark} after stress suggest increased TAT during degradation.

1. Introduction

Optical receivers based on high opto-electrical bandwidth, high responsivity and low I_{dark} waveguide-coupled Ge Vertical PIN photodetectors (PD), substantially enhance the performance of Si-based optical interconnects [1], where the performance of these PDs have been boosted by recent achievements in the epitaxial growth of Ge on Si. During operation, at nominal conditions, Ge PDs are reverse biased at -1V or -2V, and their dark current, I_{dark}, needs to remain sufficiently low to ensure a high signal-to-noise ratio of the optical receiver. The degradation mechanisms that drive the increase of I_{dark} are very complex [2-3]. This paper addresses a methodology to estimate failure rates of these components and digs deeper in the fundamentals of the degradation mechanisms.

2. Studied device and measurement methodology

We focus on vertical p-i-n waveguide-coupled Ge VPIN PDs of 2µm width, 400nm height and 13.7µm length. The doping profile in Ge was optimized for high-speed operation and low series resistance. Devices were fabricated using imec's 200 mm silicon photonics platform [4].

I_{dark} characterization and degradation was performed on imec's Process Control Monitor devices, where no circuitry was connected to the devices. Long-term stresses were enabled by dicing and wire bonding the devices in a ceramic package. The packages were then loaded in our in-house package level reliability tester where voltages can be applied and currents can be measured as a function of time at temperatures up to 200°C.

3. Lifetime assessment methodology

A methodology to estimate failure percentages of our devices has been developed and applied. We first propose ways to estimate temperature and voltage acceleration factors and then propose a method to estimate failure percentages at given use conditions.

3.1. Temperature acceleration

First, the temperature acceleration factor has been estimated using tests at different temperatures. An Arrhenius dependence of degradation with temperature T is assumed:

$$Time \sim \exp(E_a/(k_B * T)), \tag{1}$$

wherein E_a is the activation energy of degradation and k_B is Boltzmann's constant. To estimate E_a, tests at three different temperatures were performed at 2V (which is $2 \times V_{op}$ for $V_{op}=1V$ and is consistent with Telcordia [5]), where I_{dark} was measured as a function of time. Figure 1a shows the relative I_{dark} change as a function of time. In order to quantify the E_a of degradation, the x-axis has been scaled using equation (1) in a way that the degradation curves from different temperatures fall on top of each other as well as possible. For this data set, the best match was with $E_a=0.7eV$.

3.2. Voltage acceleration

Second, the voltage acceleration factor has been estimated. A power law degradation with voltage V is assumed:

$$Time \sim V^m, \tag{2}$$

wherein m is the voltage acceleration factor. To estimate m, a step stress was performed. During this test, the I_{dark} at 175°C of a number of devices was monitored. First, 1V was applied for 100h, then 1.5V applied for 100h, etc. Figure 1b shows the slope of a linear fit of the I_{dark} increase as a function of voltage. Between 1 and 2V, a linear increase of the I_{dark}-slope with voltage is observed with a 2.7-3.2x faster degradation at 2V stress compared to 1V.
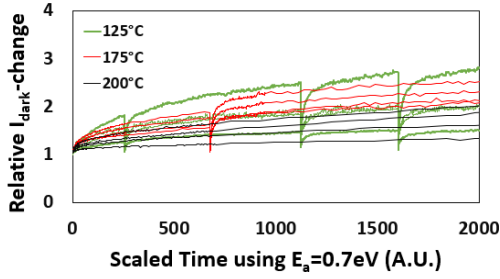
Fig. 1a: Relative I_{dark}-change with time for devices stressed at different temperatures. X-axis is scaled using eq. (1) with E_a=0.7eV
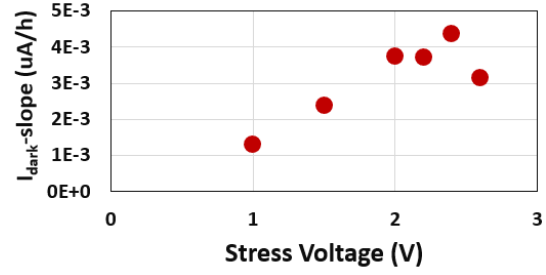
Fig. 1b: I_{dark}-slope as a function of stress voltage during a step stress at 175°C

Note that above 2V no further increase of the I_{dark}-slope is observed. We hypothesize that this observation is linked to the specific characteristics of the degradation curves of our devices (Figure 1a) where an initial faster increase of I_{dark} is observed. We argue that the slopes at voltages >2V have been obtained in the degradation region where the I_{dark}-increase was already in the later phase leading to artificially lower I_{dark}-slopes at these voltages.

3.3.   Lifetime prediction methodology

Using the acceleration factors estimated in the previous section, a 3-step lifetime prediction methodology is proposed:

1.   Given T_{op} and V_{op}, calculate the stress time t_{stress} at 175°C-2V (proposed T_{stress} and V_{stress} by TELCORDIA [5]) that is needed to mimic the required lifetime t_{req} for a certain application. This is done by plugging in the E_a and m obtained in the previous sections in formulas (1) and (2):

$$t_{stress}=t_{req}*(V_{op}/V_{stress})^m*exp(E_a/k_B*(1/(T_{stress}+273)-1/(T_{op}+273))) \tag{3}$$

An example for a specific case is worked out in table 1.

Table 1. Example of t_{stress}-calculation (E_a=0.6eV and m=2.5 is used as conservative estimates of the acceleration factors)

T_{op}	V_{op}	t_{req}		t_{stress}
90°C	1V	5y	⟹	460h

2.   Stress a number of devices for t_{stress} at 175°C-2V and measure the I_{dark} at V_{op} and T_{op} after stress.

3.   Make a cumulative plot of the obtained I_{dark} or of the obtained I_{dark}-change and determine the survival % using a given failure criterion (Figure 2). Determination of the survival % might require a bimodal fit for certain data sets.
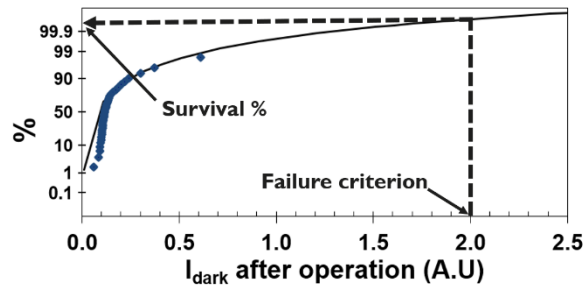

Fig. 2: Probability plot of the measured I_{dark} at V_{op} and T_{op} after stressing at 175°C-2V during t_{stress} + bimodal fit of the data

4. Degradation mechanisms

We also looked into the fundamentals of the I_{dark} degradation in our devices where we addressed the impact of voltage stress on I_{dark}-E_a and where we looked into possible recovery effects.

4.1. Lowering of I_{dark} activation energy

A lowered I_{dark}-E_a with stress time is observed, where an initial median E_a of ~0.4eV lowers to a median E_a of <0.2eV after a few 100h of stress (see figure 3). The saturating behavior over time is consistent with the saturation of the I_{dark}-increase during stress (figure 1a). The lowering of the I_{dark}-E_a is consistent with earlier reports and is potentially linked to an increased contribution of trap-assisted-tunneling to the conduction at the Ge/Si and Ge/O_x interfaces [2],[6].

4.2. Recovery effect

After stress, when the voltage is switched to 0V, a recovery of I_{dark} is observed, where for our devices an apparent recovery happens after a few hours. Figure 4 shows that, when switching on the voltage again, the I_{dark} immediately starts to increase at a faster rate compared to a fresh device (dashed versus solid line). The physics of this phenomenon could be related to the creation and passivation of dangling bonds at the earlier mentioned Ge/Si and Ge/Ox interfaces and is subject of further study.
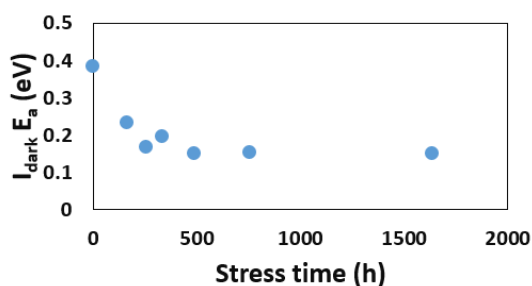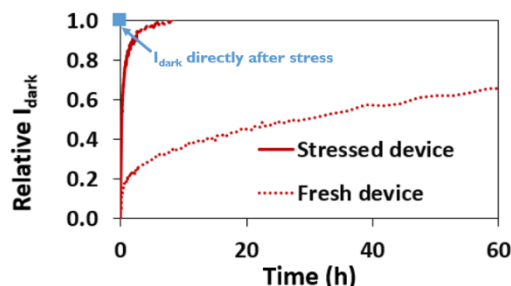

Fig. 3: I_{dark}-E_a as a function of stress time

Fig. 4: I_{dark} vs time at 200°C-2V of a stressed and a fresh device after a couple of hours relaxation at 0V

5. Conclusions

We looked in the fundamentals of the degradation mechanisms in Ge VPIN photodetectors.
First, we established a methodology to characterize failure percentages. This happened in 5 steps:
1. Estimation of temperature acceleration by fitting data at various temperatures to the Arrhenius equation. For our data set, we estimated an E_a of ~0.7eV.
2. Estimation of voltage acceleration using a step stress and by assuming a power law dependence of time on voltage. For our data set, we estimated an estimated acceleration factor of 2.7-3.2x between 1 and 2V.
3. Calculate the t_{stress} at 175°C-2V that is needed to mimic the required lifetime t_{req} for a certain application using $t_{req}*(V_{op}/V_{stress})^m*exp(E_a/k_B*(1/(T_{stress}+273)-1/(T_{op}+273)))$.
4. Stress a number of devices for t_{stress} and measure the I_{dark} at V_{op} and T_{op} after stress.
5. Make a cumulative plot of the obtained I_{dark} or I_{dark}-change and determine the survival percentages.

Second, we hypothesized that a decreasing I_{dark}-E_a with stress time was linked to an increased contribution of trap-assisted-tunneling to the conduction at the Ge/Si and Ge/Ox interfaces.

Finally, we observed a recovery effect of I_{dark}, where for our devices an apparent recovery happens after a few hours. The phenomenon is only partial in so far that the I_{dark} increase after recovery goes at a faster rate compared to a fresh device.

6. References

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