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Correlation Between the Failure Mechanism and Dark Currents of High Power Photodetectors

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ABSTRACT

We experimentally investigate the role of dark current on the failure mechanism of high power photodiodes. A theoretical model built to fit the experimental data indicates that the effective barrier height and the dark current are the fundamental parameters in the failure mechanism.

High power, high speed photodetectors (PDs) can improve overall link performance of microwave and millimeter wave photonic systems including the link gain, noise figure, and spurious free dynamic range (SFDR). Several photodetection schemes were reported that aimed at achieving high power by optimizing physical dimension, structure type and illumination conditions [1]. Although considerable power level has been achieved by several researchers, long-term reliability of high power PDs is still an unsolved issue. It is thus important to have a clear understanding of the factors that contribute to the failure mechanism of the PDs at high power operation.

There have been several investigations on the failure mechanism of high-power PDs. Paslaski *et. al.* suggested a failure mechanism of high power PDs relating it to the thermal origin [2]. Nespola *et. al* investigations suggested that PDs fail along curves of constant power dissipation [3]. However, none of the previous investigations have put emphasis on the role that dark current (I_d) plays in the failure mechanism of the high power PDs. In this paper, we report on the experimental investigation of the role of I_d on the failure mechanism of high power photodiodes. A theoretical model built to fit the experimental data indicates that the I_d and the effective bandgap ($q\phi_b$) are the fundamental parameters in the failure mechanism of high power PDs. Our investigation also shows that junction PDs (such as *p-i-n*) are expected to perform better than metal-semiconductor PDs for high power operations.

In order to demonstrate a relation between the maximum photocurrent at failure and the I_d, we tested several metal-semiconductor-metal (MSM) structures with various I_d levels. The PDs under test are velocity-matched distributed photodetectors (VMDP). Their structures have been described in [4,5]. To make a fair comparison, we chose two groups of structures - one with very low I_d (PD1) of 0.1nA/diode (0.26pA/μm^2) and the other (PD2) with high I_d of ~33nA/diode (85pA/μm^2). Both groups of PDs are monolithically fabricated on the same wafer and exhibit high linear photocurrents. Measurements of I_d were performed from 2V-12V at different temperatures from 20° to 95°C. Fig. 1 shows the I_d of both groups of devices (one sample from each group) for different temperature at 4V bias. Note that at low temperature, I_d is dominated by field emission (FE); and at high temperature, it is dominated by thermionic field emission (TFE). The slopes corresponding to these two mechanisms are also shown in Fig. 1. The variation in dark currents is caused by surface treatment before evaporation of the Schottky metals.

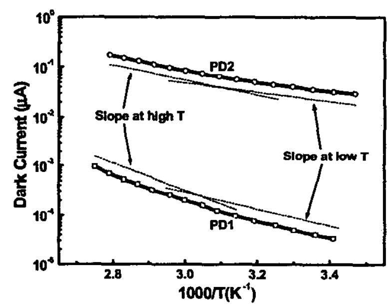

Fig. 1. I_d versus absolute temperature for PD1 and PD2 at 4V bias.

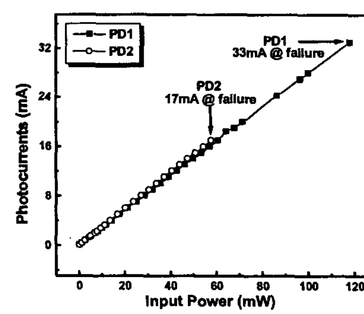

Fig. 2. Photocurents at failure for both groups of devices. In both cases PDs fail before reaching nonliearities.

When these two groups of PDs are tested for their photocurrent levels, it was found that PD1 fails at a photocurrent of 33mA when biased at 4V, generating a thermal power of 132mW (Fig. 2). A large number

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of PDs with similar I_d level were found to dissipate this amount of power at the time of failure. PD2, on the other hand, fails at an average photocurrent of ~17mA (corresponding to ~70mW power dissipation). Our measurements indicate that PDs fail along curves of constant power dissipation only when they have similar I_d at room temperature. Multiple diodes with high I_d levels were tested to reach this conclusion.

The measured I_d of our MSM based PDs is expected to obey a behavior of the form:

$$J_{dark} = J_o \exp\left(\frac{-qV}{nK_BT}\right)\left[\exp\left(\frac{qV}{K_BT}\right) - 1\right]$$

$$where,\ J_o = A^{**}T^2 \exp\left(\frac{-q\phi_b}{K_BT}\right)$$

In the above equation, n is ideality factor, A^{**} is the Richardson constant and $q\phi_b$ is the effective barrier of the metal semiconductor (MS) junction. Because of localized surface states, $q\phi_b$ is always lower than the E_g, the bandgap of the semiconductor. Using Bardeen approximation [6] we can write $q\phi_b \cong 2/3E_g$ for ideal MS contacts. Depending on the quality of the surface and process parameters, $q\phi_b$ can have lower values. The effective barrier height can be found experimentally by fitting the current-vs-temperature curve with the above equation, as shown in Fig. 3. They are found to be 0.43eV for PD1 (PD with low I_d), and 0.32eV PD2 (PD with high I_d), respectively.

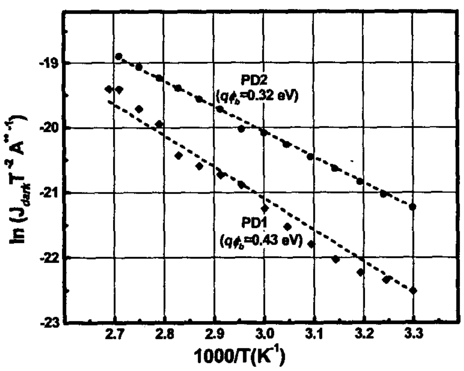

Fig. 3. Experimental data are fitted to the theoretical model (dotted lines) in order to extract the value of $q\phi_b$.

It has been shown that photocurrent produces Joule heating in the active region of the photodiode [3]. The temperature rise causes I_d to increase exponentionally, which increases temperature further. This positive thermal feedback process continues until the photodiode fails. The failure mechanism is accelerated for PD's with low $q\phi_b$. From the above equation, it is evident that PDs with high I_d are expected to have lower $q\phi_b$ and will have lower threshold of thermal damage. We have experimentally observed that PDs with high I_d fails at much lower photocurrent than those with low I_d.

Our investigation leads to the following two conclusions: (1) dark current plays an important role in the reliability of high power PDs; (2) diodes with low dark currents and high effective barriers are expected to sustain more joule heating. These observations are important for optimizing the devices and processes for high power PDs.

The reverse saturation current, J_s for a junction diode (such as *p-i-n*) is related to the bandgap, E_g as $J_s \propto \exp(E_g/K_BT)$. This indicates that the effective barrier of *p-i-n* diode is always equal to the semiconductor bandgap in the ideal case. Impurity induced trapped sites in the forbidden gap may slightly lower the barrier in the practical devices. MS contacts, on the other hand, have much lower effective barrier as mentioned earlier. Because of these fundamental differences in the characteristics and effective barrier height, the *p-i-n* photodiode is expected to have more than five orders of magnitude lower dark currents than a photodiode with a MS contact of equal active areas. Furthermore, it was shown that photodiodes with MS contact fail when the device temperature reaches 700K [3], whereas junction diodes like *p-i-n* can stand temperature above 900K [7]. Considering all these factors, it is concluded that a *p-i-n* PD with a high effective barrier and low I_d offers fundamental advantages for high power applications.

In conclusion, we observed that the effective barrier height and the dark current levels are fundamental parameters in the failure mechanism of PDs. A junction diode with a high effective barrier can sustain large amount of Joule heating and offers advantages for high power applications. It is thus important to screen photodidodes on dark currents for good reliability under high power operation. These observations are significant for understanding the catastrophic failure of high power PDs.

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