On the effect of nano-injectors on conduction in silicon p-i-n diodes.

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I. Introduction

P–i–n diodes are widely used in power electronics [1-2], solar cells [3], light detection [4] and also light generation [5]. Contrary to the case of light detection or conversion, light generation is usually achieved by biasing the device in forward mode, in a condition of carrier injection. Depending on its level, the device can operate in regimes controlled by respectively generation/recombination current, diffusion current or the so called series resistance [6]. The injection level also controls the balance between the recombination mechanisms, and it is commonly controlled via the applied bias, which could be fixed by the specific application rather then being a free parameter. A possible approach to better control the injection level is to modify the features of the carrier injectors, for instance by thinning down the junction area [7] or reducing the injectors itself to a nanometer scale [8]. A practical way to realize nano-injectors is to embed the intrinsic region in oxide and create the connection between the intrinsic region and the two extension regions via antifuses, as realized in [9]. The size and properties of the antifuses can be controlled electrically, making it suitable to analyze the effects of progressive scaling of the dimensions of carrier injectors. In this work, we compare electrical behaviors of a standard p-i-n diode with antifuse p-i-n diodes programmed at different conditions. Electrical *I-V* measurements are performed at temperatures between -20 and 200 °C (*I-V-T* characteristics) in order to investigate the dominant mechanisms in the conduction.

II. Experimental

Both standard p-i-n and antifuse p-i-n diodes are fabricated on the same SOI substrate as described in [9]. In the standard p-i-n diodes the extension regions are realized by the implantation of the electrodes. The sizes of the two devices are comparable.

The antifuse links have been initially induced in the devices by applying a constant voltage of 40 V: to avoid uncontrolled discharges, the current conduction was limited by both compliance and a 1 MΩ series resistance. Subsequently, the devices have been kept under a (low) constant stressing current until stability of the measured device resistance is

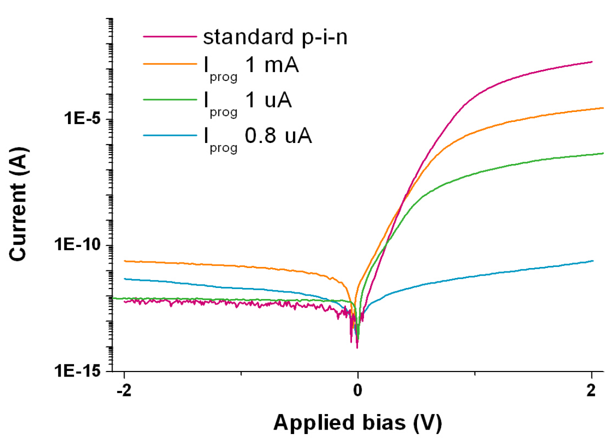

Figure 1: Measured IV (at room temperature) curves of standard p-i-n diode (red) and antifuse p-i-n diode programmed respectively at 0.8 µA (blue), 1 µA (green) and 1 mA (orange).

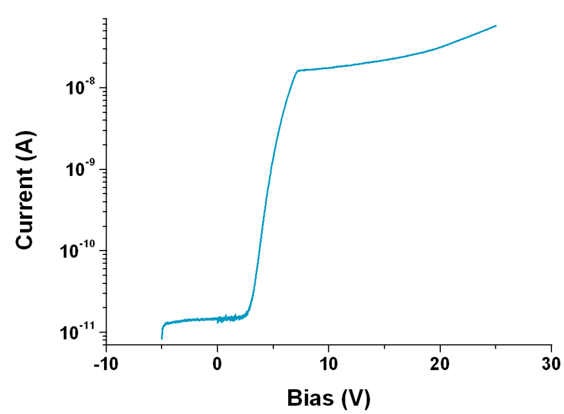

Figure 2: Semi-logarithmic IV plot over a wider range of voltages for an antifuse p-i-n diode programmed at 0.8 µA. Also see the corresponding curve in Fig. 1 for a comparison.

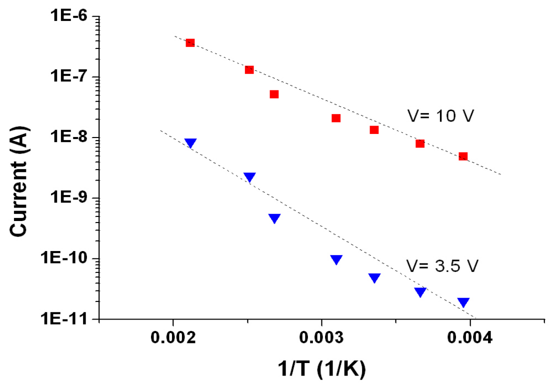

Figure 3: Example of an Arrhenius plot for devices programmed at low current (0.8 μA), for the two conduction regimes, below 7.5 V (blue triangles) and above 7.5 V (red squares). The plot shows also the linear fit for the two curves.

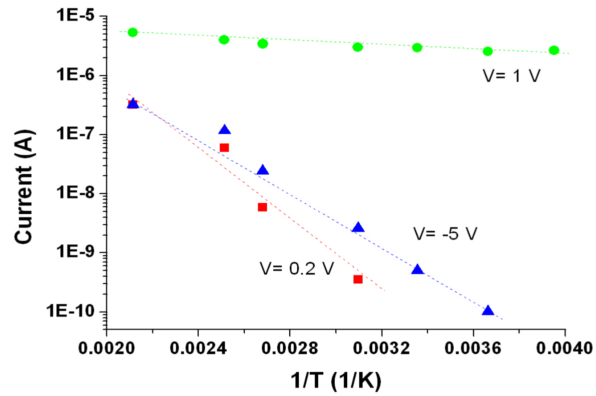

Figure 4: Example of an Arrhenius plot for devices programmed at high current (1 mA), for the G-R regime in reverse bias (blue triangles),, SRH regime in weak forward bias (red squares) and high injection regime (green circles).

observed. The current can then be increased in steps to the desired programming value, repeating the stressing procedure between two consecutive steps. A more detailed explanation of the programming procedure can be found in [10], although in the present work some steps have been modified to some extent.

The devices have been initially programmed at a low current value (i.e. the formed links were supposedly very small). Subsequently, some of the devices have been programmed further to modify the properties of the link, i.e., to determine the link influence on the device behavior. It has been observed that, once the programming current I_{prog} approaches 1 μA, the conduction of the device changes drastically, as depicted in Fig. 1. Further increase of the programming current results in less evident changes of the IV curves, approaching more and more the curve of the standard p-i-n diode. We will therefore refer to the value of 1 μA as a threshold which allows distinguishing between devices programmed at low and high current.

After being programmed to the desired current, the devices have been measured at seven temperature points between -20 and 200 °C. The effect of temperature on the conduction regimes in the devices has been described by the Arrhenius plots. The currents that were too close to the noise level have been neglected in this analysis.

III. Results and Discussion

A. Low programming current

The lowest-programming–current (i.e., 0.8 μA) devices show an *I-V c*haracteristic that deviates from the expected *I-V* shape for a p-i-n diode. The current level is low and there is not an appreciable difference between on and off state. These *I-V* characteristics are though repeatable and conduction is sensibly higher than that exhibited by the devices before the programming.

To better understand this *I-V* behavior, the devices have been measured over a wider range of applied voltages, as depicted in Fig. 2. The devices show, in forward bias, two conduction regimes. The first one is observed for a voltage below ~7.5 V, and has a slope of about 110 mV/dec. The second regime appears at higher biases, and has a much slower increase of current with voltage. From the *I-V-T* measurements the Arrhenius plots for these two regimes can be obtained. It can be observed that in both cases the plots are linear (see Fig. 3).

For such low currents (i.e., < 0.8 μA) it is plausible that the oxide is not fully broken down, or rather it is in the state often described in the literature as *soft breakdown,* in which a conduction path exists, but it has not yet a well defined structure [11]. A lot of different hypothesis have been made over the possible conduction mechanisms for soft-broken down oxides, but a general consensus has not been reached (see [11] and the references therein). Besides, none of the most recognized models would explain the exponential dependence on temperature that we observed. Therefore, the data cannot be explicitly attributed to any of the proposed mechanisms. Furthermore, this *I-V* behavior can also be caused by a combination of the mechanisms.

B. High programming current

The devices programmed at higher currents (i.e., > 1 μA) behave similarly to normal p-i-n diodes and exhibit standard regimes of conduction. The devices show an appreciable on-off ratio and the current level for the high-injection regime increases with increasing programming current. The latter is expected due to the increase of conductivity of the antifuses. For all the regimes, the Arrhenius plots are linear, as depicted in Fig. 4 for a device programmed at 1 mA.

The temperature dependence, while applying a reverse bias, is characterized by a slope of ~0.63 eV for all the devices, regardless the programming current value. The same value is obtained also for the reference p-i-n diode, which is consistent with a generation-recombination (G-R) based conduction in the intrinsic region.

For a low forward bias (never exceeding 0.4 V), the slope of the Arrhenius plots is almost constant for all the device, and comparable with that extracted for the reference p-i-n diode. The value varies between 0.42 and 0.44 eV, showing a weak trend to decrease with increasing applied voltages. Both observations point to the Shockley-Read-Hall (SRH) recombination mechanism dominating the current. Such an assumption is confirmed also by the value of the slope of the *I-V* curves. This results in ~120 mV/dec for the mentioned voltage range.

With further increasing the bias, the devices enter the regime generally attributed to the series resistance: in this case the effect of the temperature is not very well pronounced. Different programming conditions affect the current-voltage onset of this regime and the series resistance value. The lower the programming current, the less conductive the link is, which results in a higher resistance component and an earlier (with respect to the bias) roll off of the current.

IV. CONCLUSIONS

In this work, we explored the role of the antifuse-based nano-links as carrier injectors. Their influence on the current-voltage behavior of the p-i-n diode was studied.

A low programming current (i.e., 0.8 μA) results in a lower conductivity of the links and is a factor limiting the diode conduction. Attribution of the conduction to a specific mechanism is difficult; however the current dependence on temperature is observed to be exponential.

A high programming current (i.e., > 1 μA) results in a close-to-conventional p-i-n diode behavior. The latter means a generation-recombination regime in reverse, a SRH regime in weak forward, and a current limited by series resistance for high-injection regime.

The conduction mechanisms could be consistently identified for each regime, based on both the analysis of *I-V* characteristics and the Arrhenius plots. The latter resulted in the clearly-observed linear behavior for all the conduction regimes. The main impact of the nano-links was observed on the series resistance, and thus on the current value for the high-injection regime.

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