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Titouan Legoff, Florent Rochette, Olivier Gravrand, Nicolas Baier, Clément Lobre, et al.. Discussion on diffusion current suppression in HgCdTe MWIR detectors. Proceedings of SPIE, the International Society for Optical Engineering, 2023, Infrared Technology and Applications XLIX, 12534, pp.125340Q. 10.1117/12.2663816 . cea-04575250

HAL Id: cea-04575250

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Submitted on 14 May 2024

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SPIE.

Event: SPIE Defense + Commercial Sensing, 2023, Orlando, Florida, United States

Discussion on diffusion current suppression in HgCdTe MWIR detectors

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ABSTRACT

One limitation of dark current for HOT HgCdTe MWIR detector is diffusion current related to Auger generation mechanisms. However, this limit can be overcome using a fully depleted P-i-N diode structure. On the way toward PIN structures, we discuss on the impact of Auger suppression on partially fully-depleted photodiodes. Indeed, we report dark current evolution with temperature following a diffusion trend line but also a dark current decreasing when increasing the applied voltage in the temperature range 120-180K on the same detector. If the SRH current in the space charge region is very low, an Auger suppression mechanism should result in a decrease of the total dark current when depleting a larger volume of the pixel on such detector. This hypothesis could match with the reported dark current data obtained on detectors manufactured at CEA LETI and Lynred. They are based on p/n diodes, 7.5 μm pitch arrays connected as 2x2 super-pixels to a 15 μm pitch ROIC (640x512 VGA format).

Keywords: IR detector, HgCdTe, Auger suppression, fully depleted p-n junction, PIN, MWIR, HOT.

1. INTRODUCTION

A new generation P on N technology MWIR detectors with MCT material for high operating temperature (HOT) application is developed at CEA LETI and Lynred [1], [2]. Concepts for HOT Focal Plane Array (FPA) require lowering the dark current of the absorption layer to limit shot noise and increase the dynamic range of the signal of concern for reasonable integration times. Since dark current may be limited by Auger lifetime in classical diffusion limited HgCdTe IR detectors [3], a first path for minimizing dark current is to maximize the doping-Auger lifetime product, for instance using extrinsically P doped MCT [4], [5]. On the other hand, a more radical solution is to remove diffusion current from the device with fully depleted P-I-N or Auger suppressed diodes [6], [7]. Classical lifetimes of SRH currents on devices designed and manufactured at CEA LETI where on the 10-100 μs range [8], but very long lifetime have been reported for this mechanism, longer than the millisecond [9], [10], consequently much longer than Auger diffusion lifetime. Unlike Auger lifetime, SRH recombination is an extrinsic lifetime mechanism and can be improved by technological means. The expected gains with these structures would be a large increase of the operating temperature of the FPA (up to 40K) with limited performance degradation [11].

Still, all these improvements require doping levels lower than 10^{15}cm^{-3} range to obtain the full benefit of the Auger suppression mechanism. We investigate here what could be considered as a transitory structure to investigate Auger suppression, using new generation P on N 7.5 μm pitch diode technology from CEA LETI and Lynred, presented at this conference [2]. The doping level is in the 10^{15}cm^{-3} range, but is low enough and SRH lifetime long enough with this improved technology to observe the beginning of Auger suppression.

2. EVIDENCE OF AUGER SUPPRESSION ON FOCAL PLANE ARRAY (FPA) AND CONFINED SINGLE TEST DIODES

2.1 FPA data

Devices under test are FPA with 7.5 μm P/N diode hybridized 2x2 on 15 μm pitch ROIC 640x512 pixel using Direct Injection architecture. Figure 1 illustrates such a super-pixel. The current measured on a pixel of this FPA is then equivalent to the expected current of a 15 μm pitch photodiode.

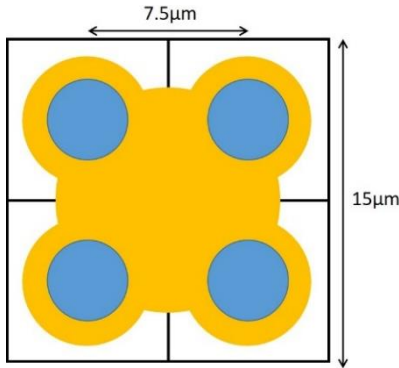


Figure 1 : Scheme of a pixel from 15 μ m pitch FPA : four 7.5 μ m pitch diodes from the MCT detector layer are hybridized on a single 15 μ m pitch ROIC. The total FPA size is 640x512 super-pixels.

Single arrays also include several diode geometry flavors, distributed as 160x128 pixels variant areas on the FPA. Mapping on Figure 2 shows dark current at 180K on a full array with the 16 areas corresponding to 4 different diode geometries delimited. Different diode geometries are distributed on the array in a way that we can distinguish non-uniformity on the array to the proper impact of the diode geometry. Figure 2 presents results of I(V) characterization in dark conditions for some variant, ordered by increasing diode geometry. A current gradient is present across this FPA, with higher current for the variants at the bottom of the array, but geometry contribution on dark current is greater than the gradient.

Two points can be underlined: the dark current decreases when the diode geometry increases for a given applied voltage and the dark current decreases with increasing applied voltage for a given diode geometry, resulting on a negative dynamic resistance. Moreover, this negative slope is steeper for larger diode geometries. The current decrease is below 3% for smaller diode geometry and close to 20% for the greater ones. An explanation for both behaviors is that larger geometry or deeper depletion volume with applied voltage reduces the diffusion volume of the diodes. It would therefore be a first sign of Auger suppression process.

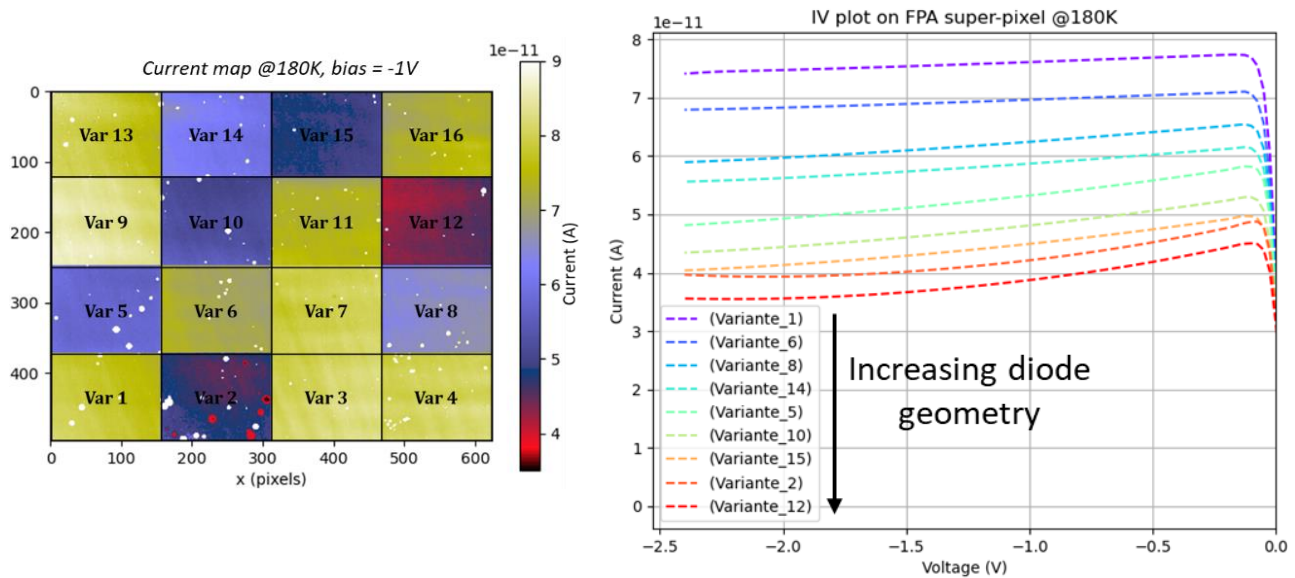


Figure 2 : Current map of FPA with super-pixels #1 at 180K and -1V bias (left) and median I(V) plot of some variants (right).

2.2 Confirmation on single confined diode

To exclude any effect attributed to the super-pixel hybridization on the FPA, we measured dark current on single diode test structures that are true 7.5 μ m pixel pitch. These test diodes are surrounded by two rings of diodes whose applied voltage follows the bias applied to the central diode of interest. Consequently, the collection volume of the test diode is

similar to the collection volume of a diode in a FPA. Figure 3 plots the I(V) curve of this device, where the diode geometry is similar to variants 8 and 14 of the previous full array #1. The same I(V) shape is present on this test structure, but with a smaller current decrease of 4% compared to a 6-8% decrease on variant 8 and 14. The difference could be due to the current estimation on the FPA. Current on a FPA variant is the median value of the current on a 160x124 pixels sub-area while it is a single shot measurement for test diodes.

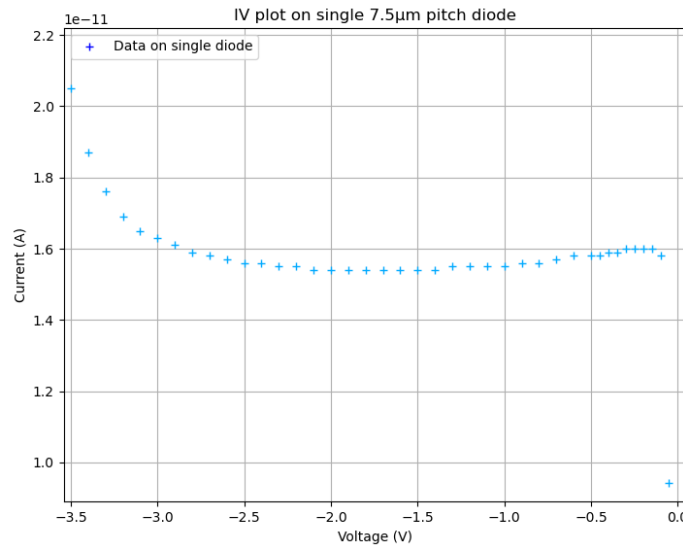


Figure 3 : I(V) plot of a single confined 7.5µm pitch diode at 180K. The corresponding geometries on FPA #1 are variant 8 and 14.

We report on two different test structures and independent data a negative dynamic resistance on 15µm pitch super-pixel FPA and single confined 7.5µm pitch diode. An additional effect on FPA data including diode geometry flavors is that the current decreases as the geometry increases. In an attempt to interpret these observations, the next section develops a current model including Auger suppression mechanism.

3. CURRENT MODEL

In a first approach to explain FPA and single diode data, a model with simple planar diode geometry, represented on Figure 4, Auger and SRH diffusion and SRH depletion current is used [12], [13], [6].

The pixel has a given thickness $t_{layer} = 4\mu m$, the P doped layer thickness is neglected, the space charge region (SCR) spreads in the N-MCT layer by the W_{dep} length and the diffusion layer thickness is equal to the pixel thickness minus the SCR size. This model is valid if the diode has a size comparable with the pixel pitch and the diffusion layer thickness is not too large compared to the space charge region.

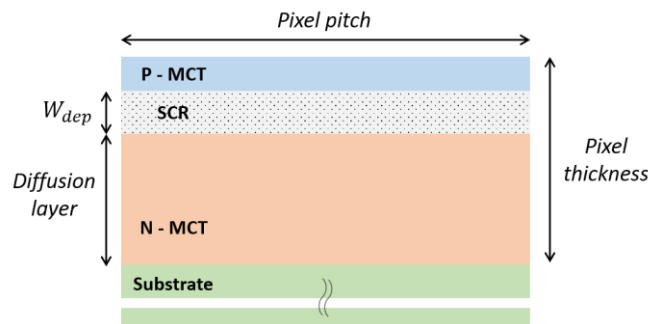


Figure 4 : Planar diode geometry used for the current model. The current of the P layer is not taken into consideration. The space charge region spreads in the N MCT layer by the length W_{dep} . The diffusion layer length is then equal to the pixel thickness minus the space charge region.

Total current in the structure can be divided on three main contributions, Auger and SRH current in the diffusion layer and SRH current in the SCR. Considering currents in the N doped layer only, the current terms are:

$$I_{Auger} = \frac{qn_i^2}{N_D\tau_{A1}}(t_{layer} - W_{dep})p^2 \quad (1)$$

$$I_{diff\ SRH} = \frac{qn_i^2}{N_D\tau_{SRH}}(t_{layer} - W_{dep})p^2 \quad (2)$$

$$I_{dep\ SRH} = \frac{qn_i}{\tau_{SRH}}W_{dep}p^2 \quad (3)$$

And the total current:

$$I_{tot} = I_{Auger} + I_{diff\ SRH} + I_{dep\ SRH} \quad (4)$$

With p the pixel pitch, q the elementary charge, N_D the doping in the N region, t_{layer} the thickness of the absorbing layer, τ_{A1} the Auger 1 lifetime and τ_{SRH} the Shockley-Read-Hall recombination lifetime. The same τ_{SRH} is used to model the SRH current in the diffusion layer and in the SCR. For reference of the expression of Auger 1 lifetime, see [13].

The doping level N_D and the SRH lifetime τ_{SRH} are the parameters of main interest in the model. Their impact on the total current can be investigated through current-voltage and current-temperature plots. Figure 5 illustrates the contribution of the doping level on I(V) curves for planar photodiodes. With N_D in the high $10^{15}cm^{-3}$ range, the Auger suppression is barely visible. Now if N_D is in the low $10^{15}cm^{-3}$ range, a current decrease of 20% can be expected with a -4V bias. Continuing to decrease the doping level reduces further the Auger diffusion current, but depletion SRH contribution would limit the current decrease even with a $\tau_{SRH} = 1ms$. The SRH lifetime must therefore be longer than the millisecond to have a full benefit of Auger suppression mechanism.

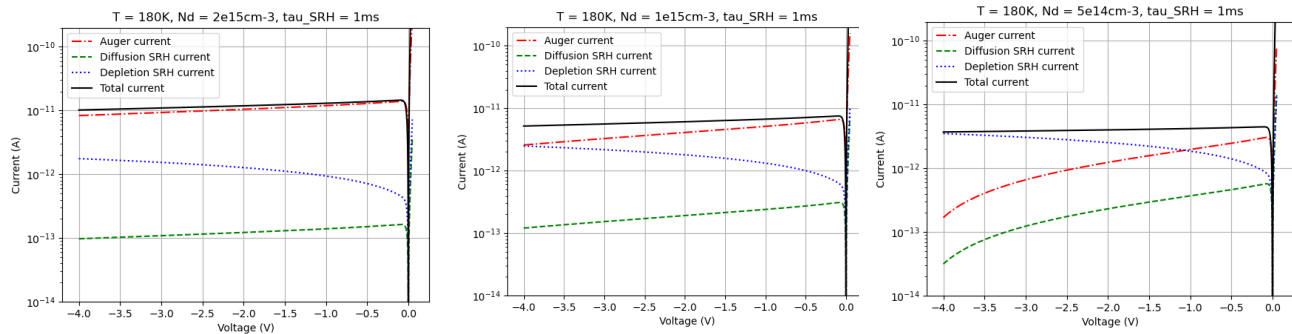


Figure 5 : I(V) plot according to the Auger suppression model with a simple planar diode geometry. From left to right are the same plots but using a decreasing N doping, at constant operating temperature 180K and with a constant SRH lifetime $\tau_{SRH} = 1ms$.

Figure 6 explores the contribution of SRH depletion current at low temperature with an I(T) Arrhenius plot. Once again with a SRH lifetime equal to 1 ms, the SRH depletion current dominates at temperatures below 130K, which is the target operating temperature for 7.5 μm pitch FPA at CEA LETI and Lynred. However, this SRH lifetime would be long enough to allow operation at higher temperature in the case of fully depleted diodes. Still, with the doping level used for this technology, this figure shows that the expected dark current is lower than predicted by the Rule07, which is in good agreement with diffusion limited model [14]. Finally, the diffusion SRH current contribution should remain negligible compared to Auger Diffusion current at high temperature and SRH depletion current at low temperature. This is the consequence of using the same SRH lifetime in the diffusion and depletion region.

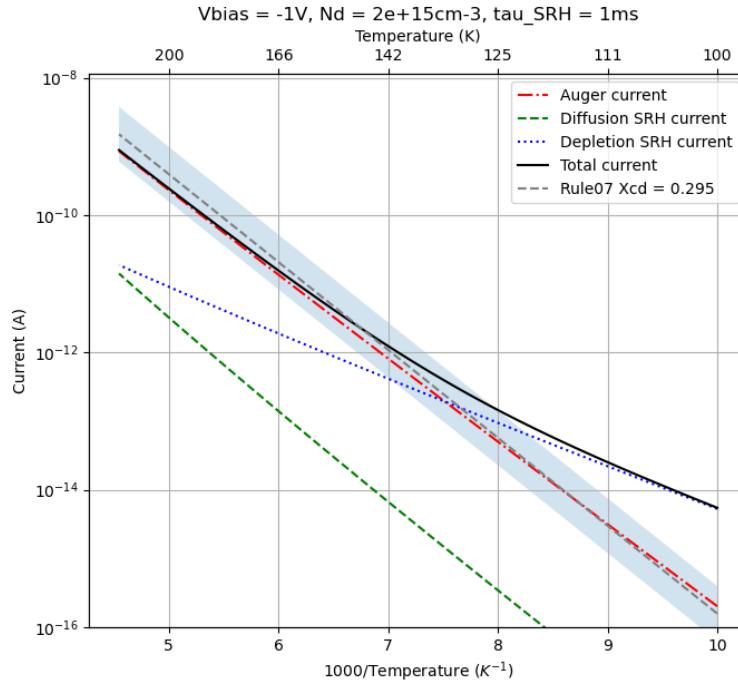


Figure 6 : Arrhenius plot of the three current contributions to the total current of the Auger suppression model with a planar diode geometry. With a N doping in the low 10^{15}cm^{-3} range and a SRH lifetime of 1ms, this later contribution should become dominant around 130K.

4. AUGER SUPPRESSION MODEL COMPARISON WITH FPA DATA

4.1 Temperature dependence and SRH lifetime estimation

In the following, current measurement from only the larger diode geometry of the FPA are compared to the model. Indeed, the validity of the model holds only if the diode structure is close to a planar junction. Current on smaller diode geometry investigated with the FPA and single confined diode tends to diverge from the current estimated by the planar diode model.

The most direct method to extract SRH lifetime with the model is a current-temperature Arrhenius plot as shown on Figure 7. The doping N_D , the SRH recombination lifetime τ_{SRH} and the overlap integral $f_1 f_2$ of the Auger lifetime are free parameters to adjust current data as a function of operating temperature. The figure plots dark current data of two FPA, manufactured from two different batches, and best estimation of Auger diffusion current, SRH diffusion and SRH depletion currents.

Data at low temperature are in good agreement with SRH lifetime longer than the ms, respectively 4ms for FPA #1 and 20ms for FPA #2. On the later FPA, the dark current should remain in a diffusion-limited regime down to 100K. At intermediate temperature, from 120K to 180K, Auger diffusion current dominates the total current. Then for high temperature above 200K of FPA #2, the model seems to underestimate current data. Measurement at higher temperature would have been necessary, but an explanation could be that the SRH lifetime is not the same in the diffusion region than in the depletion region as stated in the model. Indeed, SRH lifetime depends on the position of the trap energy level relative to the Fermi level in the bandgap, which is close to the conduction band in the neutral region and close to mid gap in the space charge region [15].

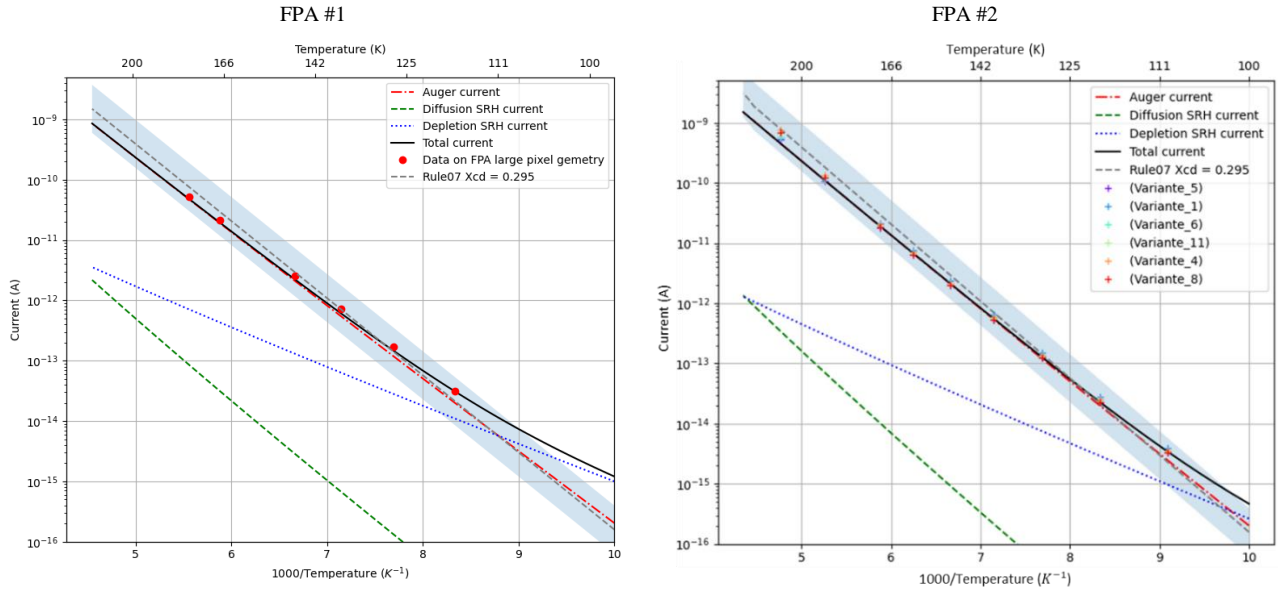


Figure 7 : Arrhenius plot of median current at -1V of two 15 μ m super-pixel pitch FPA and best fit of current model. The best estimated SRH lifetime is $\tau_{SRH} = 4ms$ for FPA #1 and $\tau_{SRH} = 20ms$ for FPA #2. These two FPA come from different batches.

4.2 Auger suppression on IV plots

Using the SRH lifetime estimated in the previous section, Figure 8 plots IV curves of the larger diode geometry from FPA #1 at several temperatures. With a single doping level and $f1f2$ overlap integral, the model is in good agreement with data on a 40K temperature range. The model covers better IV curves at higher temperatures (where diffusion current dominates) than data at lower temperature and lower applied bias.

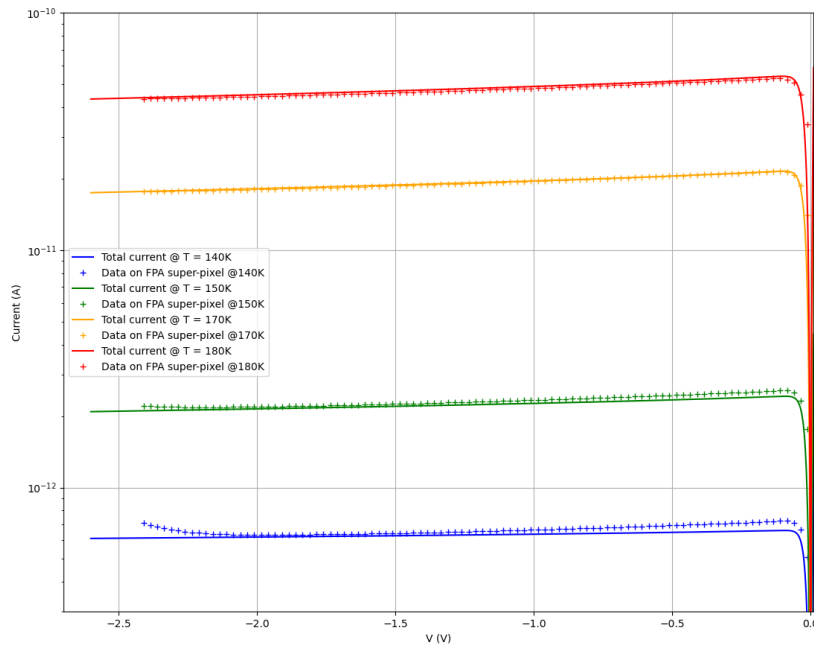


Figure 8 Log scale I(V) plot of median current of variant 12 FPA #1 and best estimation with the current model at 140, 150, 170 and 180K. The same fitting parameters N_d , $\tau_{SRH} = 4ms$ and $f1f2 = 0.18$ are used to adjust the I(V) curves.

5. CONCLUSION

This paper reports current-voltage characteristics with negative dynamic resistance, usually attributed to Auger suppression mechanism on FPA and confined single diode with doping in the 10^{15}cm^{-3} range. These devices are not design to specifically enhance this phenomenon yet. To investigate the hypothesis of Auger current suppression, a simple model is presented, considering a planar diode geometry, Auger diffusion current, SRH diffusion in the N neutral layer and SRH depletion current in the SCR. This model shows good agreement with dark current data as a function of temperature in the 110-200K range and corresponding current-voltage characteristics. According to the model, data at low temperature are compatible with SRH lifetime of 20ms. Dark current on FPA with this SRH lifetime remains in a diffusion-limited regime down to 100K. Because it is a 1D modelling, one limit of this model is that it does not correctly fit all the operating temperature for very small diode geometries. An improvement of the model should be to consider current collection on the sides of the diode in addition to the collection under the junction.

This analysis with FPA having doping in the 10^{15}cm^{-3} range presents the interest to be in a transitory regime, where diffusion current dominates at high temperature, but the beginning of Auger suppression can be observed. These first results of very long SRH lifetime on new P on N technology FPA manufactured at CEA LETI and Lynred are encouraging for the development of low-doped structures in the path for PIN photodiodes.

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