# Increasing Light Detection Efficiency of SiPMs using TSVs

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The complex circuitry attached to a p-n juction diode, to make it function as a SiPM, causes excessive crowding on the top electrode. This obstructs the passage of light and reduces efficiency. With the introduction of conductor bars (TSVs) into the bulk of Si, the active circiut attached to the top electrode, can now be placed at the bottom of the SiPM and still have an electric contact with the top electrode. Thus, have more efficiency.

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# 1. Introduction

An SIPM is a p-n junction diode engineered to detect photons. It does the same work as a Photo-Multiplier Tube but has multiple advantages over the later, such as extremely small size etc. A p-n junction when reverse biased to small voltages, produces a very small current, due to the flow of minority carriers. But, when this reverse voltage is increased to values above breakdown, the minority carriers gain high energy and cause collisions that ultimately result in the formation of new charge carriers. These new carriers, in turn continue the cascading effect and thus a very high current is established.

It should be noted, to initiate this avalanche process, an initiator such as thermally or photo generated carriers is required.

## 1.1. Structure and Electronic behaviour of a SiPM diode

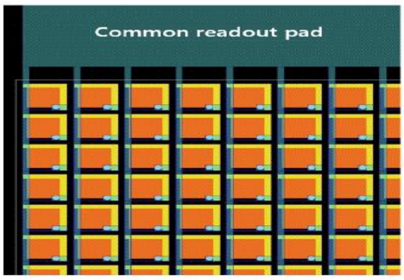
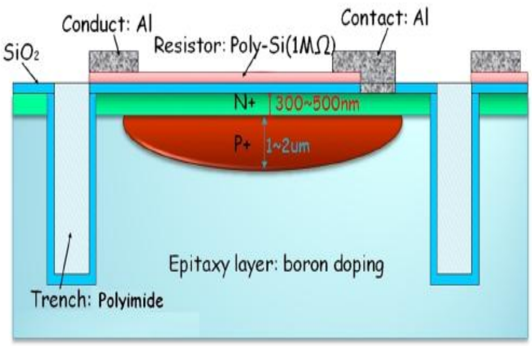



Fig.1: SiPM array Ref[1]

The SiPM utilizes this basic principle of reverse bias p-n junction, and is triggered when
1) exposed to light and
2) biased above breakdown.
But, there are some limitations.

1) Since the output of a single SiPM diode is same, irrespective of the number of photons hitting, an array of micro-sized diodes are connected in parallel. This is done to obtain a current proportional to the number of pixels activated. Thus, an estimate of number of photons hitting the array can be made. Of course, the assumption here is that every pixel is hit by a single photon or same number photons, which is true to a great extent when we have small sized pixels. But this is maximum that the present technology can do.
2) Also, to ensure that the activated pixel is quickly deactivated, so that it is available for next detection, a resistor is connected in series to quench the voltage across the diode and bring it quickly back to below breakdown.



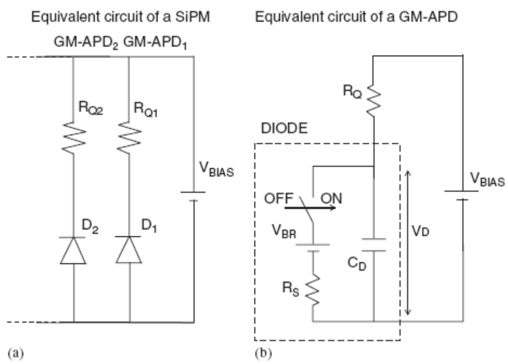




Fig. 2: Crowded top electrode Ref[1]

Fig. 3: Electrical Model of SiPM Ref[2]

Fig. 3 is the most general way an SiPM is modelled into an electrical circuit [2]. The region within the dashed lines is the diode, and outside is the external circuitry that includes quench resistor $R_Q$. The diode is modelled as a resistor, capacitor, battery of voltage $V_b$ (breakdown voltage) and a switch all connected in series. The pre breakdown situation can be represented as a capacitor connected in series with the quench resistor. As more and more charge accumulates on the capacitor, it's voltage increases beyond breakdown and then depending on some probability (called 'probability of avalanche'), the key switches on and the capacitor starts discharging. Thus, a large current starts flowing through the quench resistor and this increases the voltage across it. As a result, the voltage across the diode drops below breakdown and avalanche is quenched.

### 1.2. The Problem

In order to
1) gain full control over individual pixels of an SiPM and,
2) enable each pixel to record consecutive avalanche events,
one needs to attach a great deal of circuitry like quench resistors and/or active CMOS to the individual pixels of the SiPMs. Since bottom electrode is common to all pixels, the individual circuit elements need to be attached to the top electrode. This obstructs light and reduces effective area of availability of the silicon for avalanche.

### 1.3. The Solution

The solution suggested by my mentor (Gregorz Deptuch, ASIC group, Fermilab), is to insert a bar of conductor through the silicon bulk and use it to establish an electrical contact between the top electrode and pixel specific circuitry at the back end of the SiPM diode. Of course it is insulated from the bulk of silicon by a layer of $SiO_2$. However, there are some obvious fears about the solution. The insertion of a conductor into silicon may distort the original electric field, and other field related parameters, inside the diode and thus in turn affect breakdown or avalanche of the SiPM. The purpose of my project is to check the feasibility of this idea. The bar of conductor is called Through Silicon Via (TSV).

## 2. Simulation Specifications

For my simulations, I have used Silvaco as a software and ‘Geiger’ and ‘consrh’ as physical models. ‘consrh’ stands for recombination mechanism ‘Shockley Read Hall’ with dopant dependent carrier lifetime . Geiger is a model developed by Silvaco for simulating events at reverse breakdown of diodes.

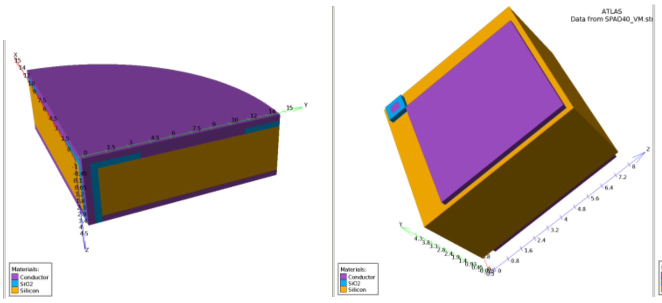


Fig. 4(a): Cylindrical and Cubical 3D structures. The TSV in case of cylinder is at the center and in cuboid it is at a corner.

### 2.1. Simulated structure of SiPMs

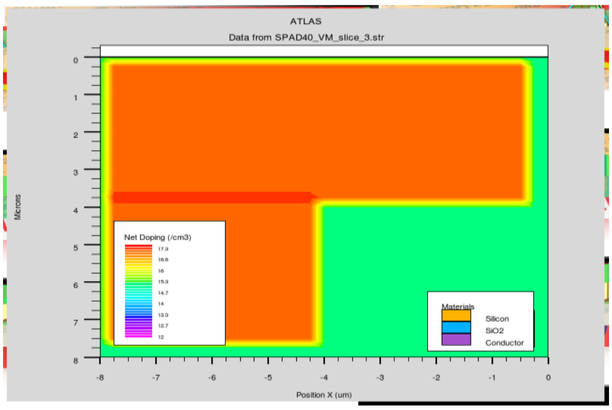



Fig. 4(b): 2D cross sections of the Cuboid in fig. 4(a)

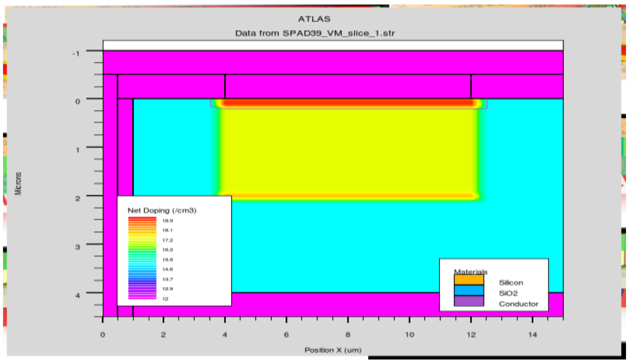



Fig. 4(b): 2D cross sections of the Cylinder in fig. 4(a)

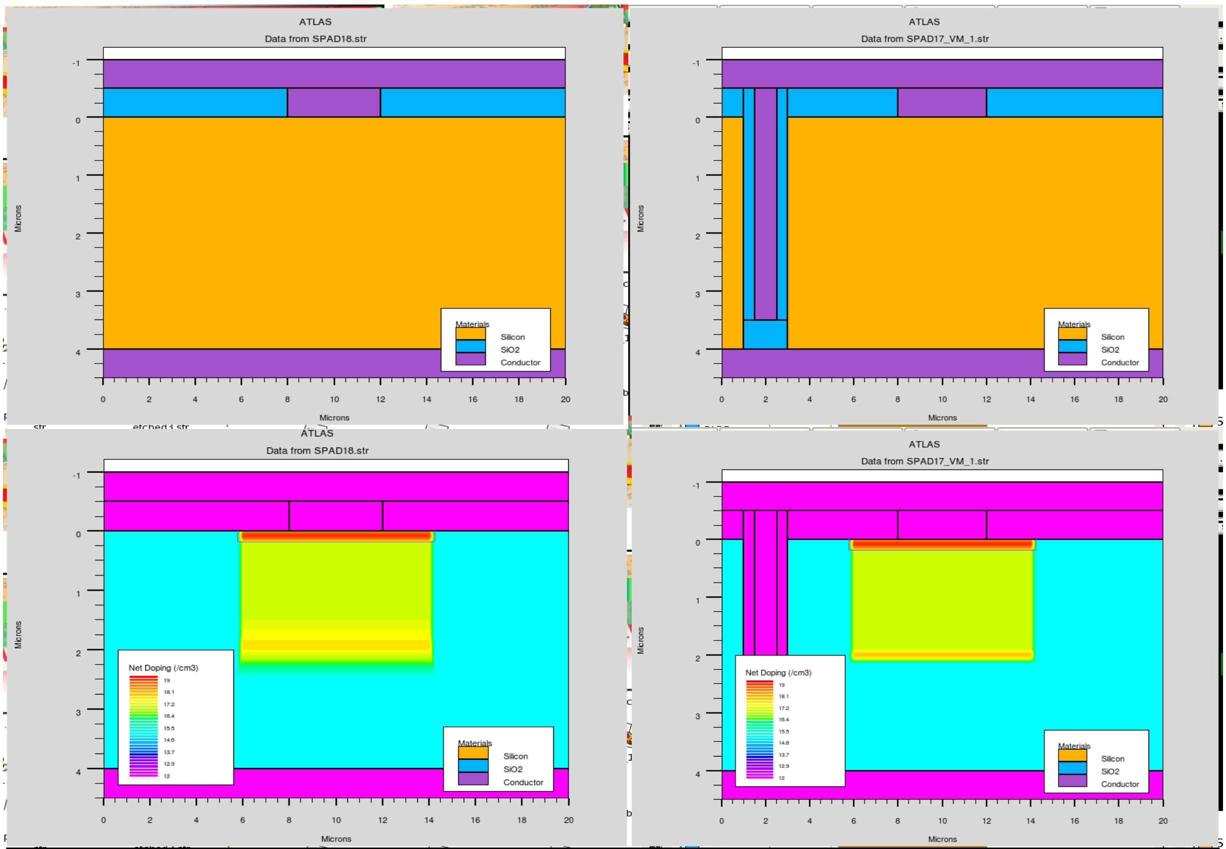



Fig.5: Typical 2 D structures used for analysis. Left ones are without TSVs and the right ones have TSV. The lower figures indicate doping. The Red part has a n-doping of $10^{19}$ and green ones are p of $10^{17}$. The rest of the silicon has a doping of $10^{15}$

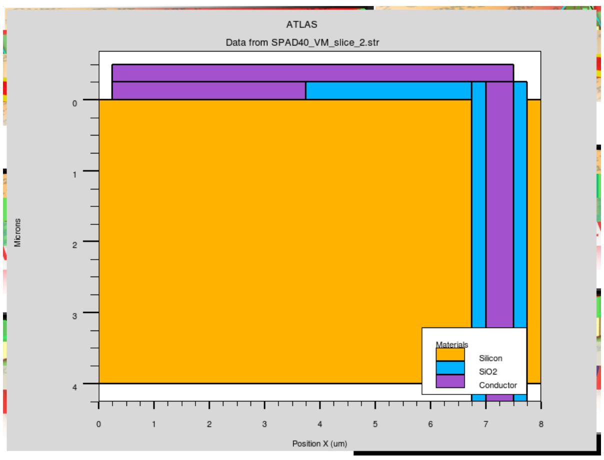



Figure 4(a) are simulated 3D SiPM structure and figure 4(b) shows it's 2D cross sections. It has a TSV inserted at one corner and the silicon bulk has been doped, maintaining a distance of 2 microns from the TSV. During the project, I have simulated 2D cross sections for electrical measurements and then applied the same on some 3D structures. The 2D structures have a doping profile as shown in Fig5. However, there are slight variations in different designs.

Figure 6(a) and (b) depict the hole and electron concentration at breakdown of the 2D SiPM shown in fig.5. As you can see the depletion region near the junction (shown as line in plots) has some concentration of carriers which are created as a result of the avalanche process. Fig 7(a) depicts avalanche breakdown as the I-V characteristic of the SiPM pixel and 7(b) is recombination rate of carriers using default parameter values of Silvaco model ‘consrh’.

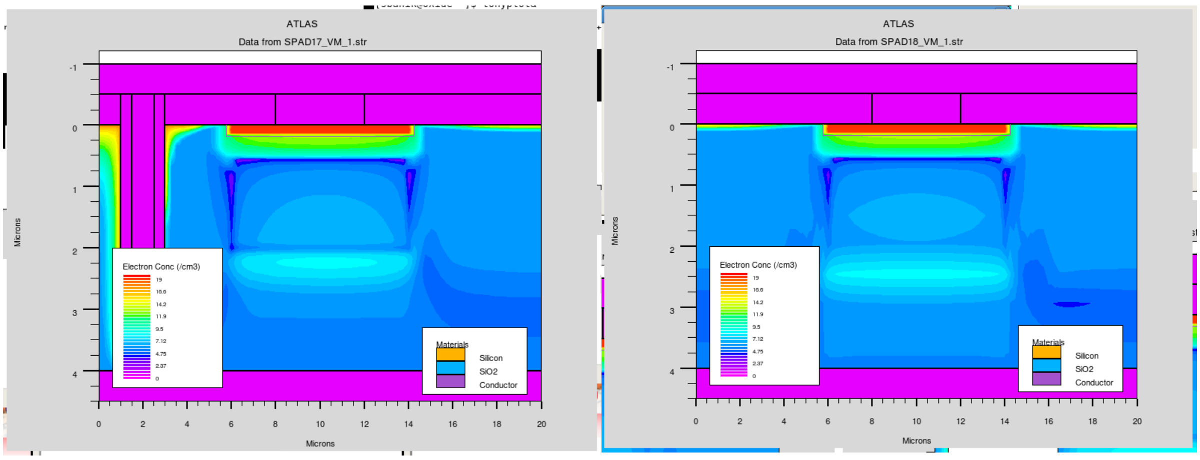



Fig. 6(a): Electron Concentration at breakdown

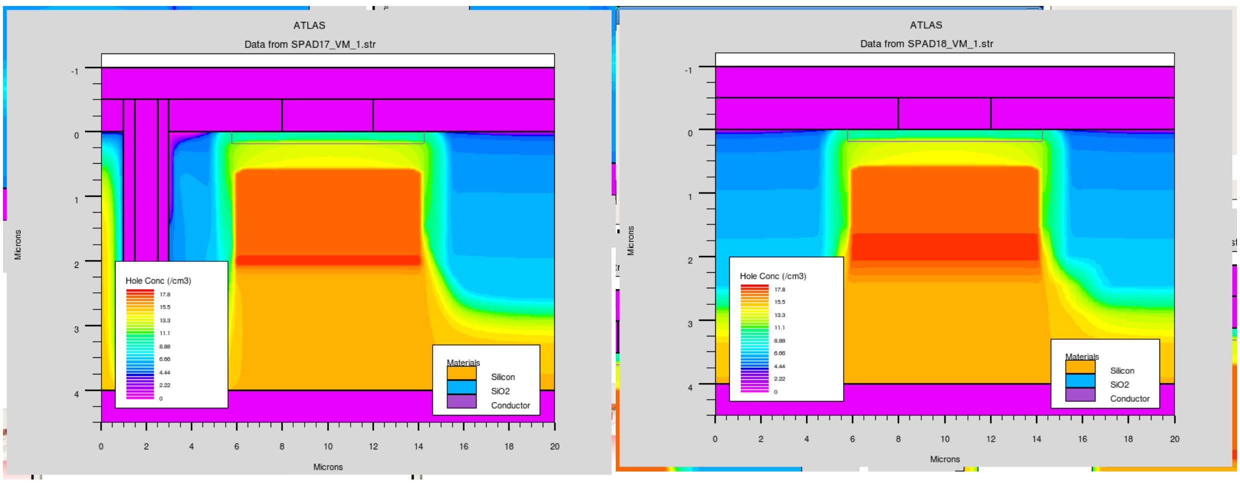



Fig. 6 (b) Hole Concentration at breakdown

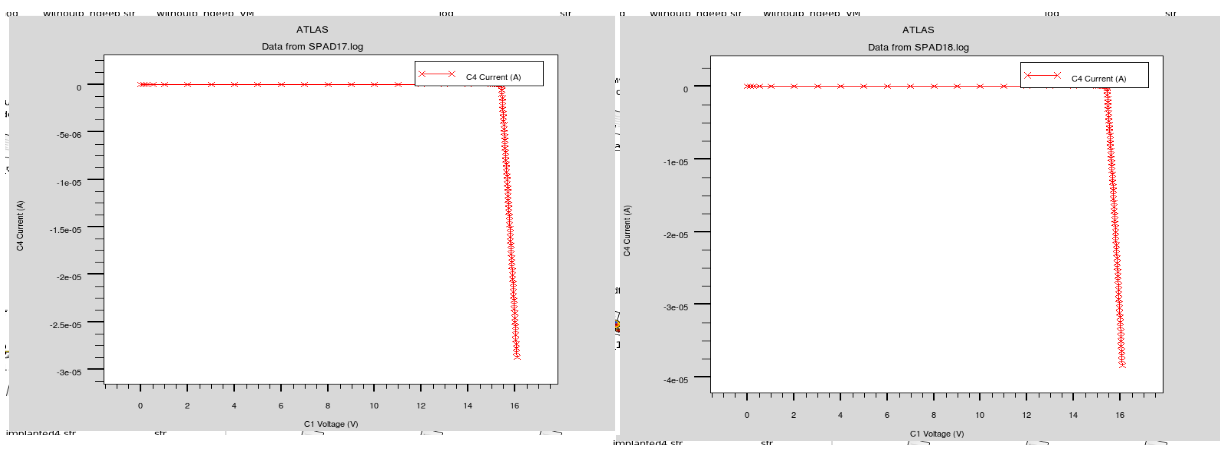



Fig. 7(a) : I-V Characteristics

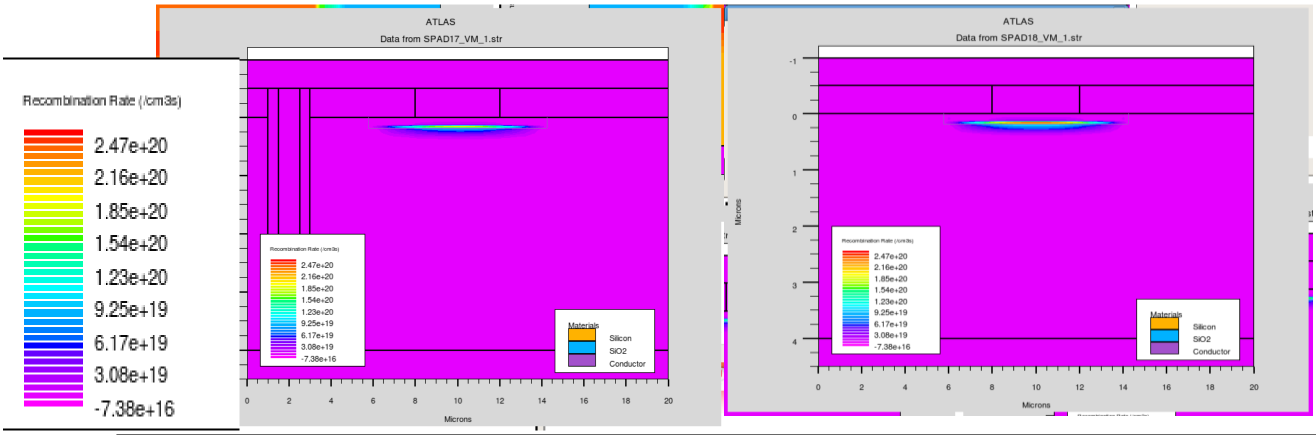



Fig. 7(b) : Recombination rate at breakdown.

## 2.2. Playing around with recombination model 'consrh'

This built-in Silvaco models uses the following equation for recombination rate and incorporates a carrier lifetime dependent on concentration. So, the recombination rate $R_{SRH}$ is given by

$$R_{SRH} = \frac{pn - n_{ie}^2}{\tau_p\left[n + n_{ie}exp\left(\frac{ETRAP}{kT_L}\right)\right] + \tau_n\left[p + n_{ie}exp\left(\frac{-ETRAP}{kT_L}\right)\right]}$$

where:

$$\tau_n = \frac{TAUN0}{AN + BN\left(\frac{Ntotal}{NSRHN}\right) + CN\left(\frac{Ntotal}{NSRHN}\right)^{EN}}$$

$$\tau_p = \frac{TAUP0}{AP + BP\left(\frac{Ntotal}{NSRHP}\right) + CP\left(\frac{Ntotal}{NSRHP}\right)^{EP}}$$

Where
p=hole conc.  n=electron conc.
ETRAP = Energy of the trap for recombination
$T_n$ = electron lifetime
$T_p$ = hole lifetime
AN, AP, BN, CN, CP, EN, EP are constants
I tried varying the value of taun0 and taup0 and then looked into the recombination rates at different locations in the structure. The recombination rate depends on

1) Carrier concentration (directly and also carrier lifetime is dependent on concentration)
2) And the carrier lifetime

If a breakdown occurs, the recombination rate will be maximum at the junction because huge amount of charge carriers are created there. This is evident in fig 7(b) which is the recombination rate plot for a SiPM structure at breakdown. Figure 9, which is recombination rate plot for a structure with extremely small values of carrier lifetime (~$10^{-14}$), doesn't achieve breakdown. Here, since no extra carriers are produced, the junction being in the depletion region has a lower recombination rate.
According to fig.8, if the carrier lifetime is reduced excessively ($10^{-13}$s), recombination rate at the junction reduces. The cause could be a recombination time, shorter than time between collisions.This will reduce the number of carriers in the conduction band that can travel towards the junction and cause avalanche. Thus the electron and hole concentration at the junction are affected which in-turn changes the recombination rate. However, it is not very clear as to how Silvaco simulates these processes in the breakdown region where continuity equations are not valid.

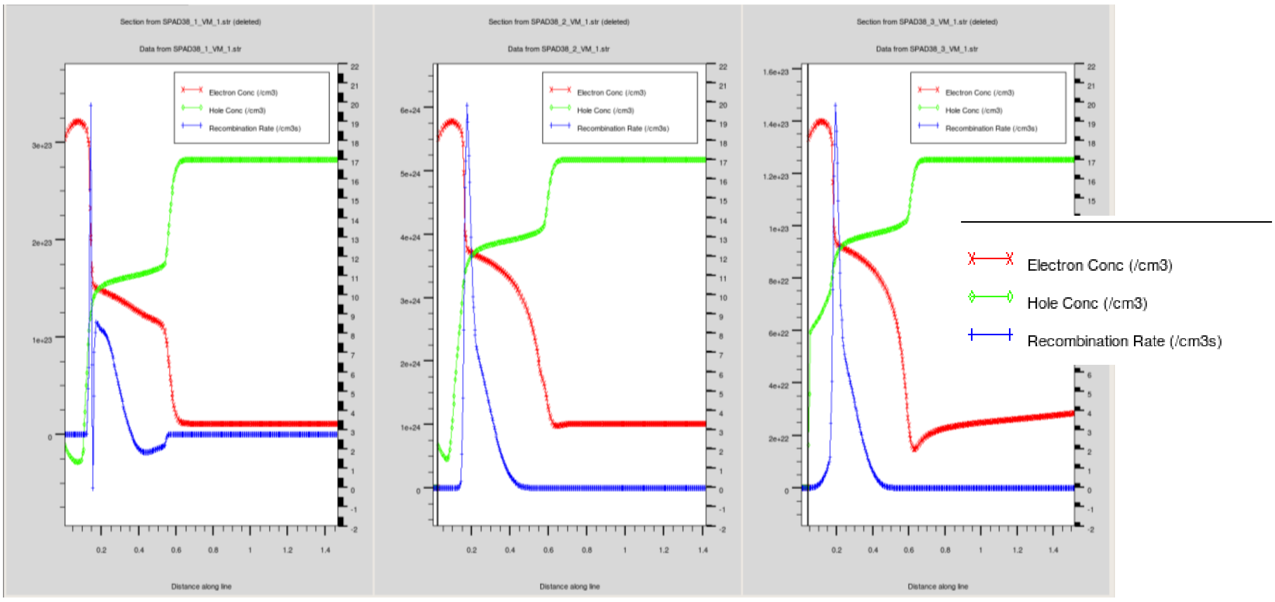



Fig. 8 : taun0 and taup0 values -> $10^{-13}$s, $10^{-12}$s &$10^{-10}$s respectively

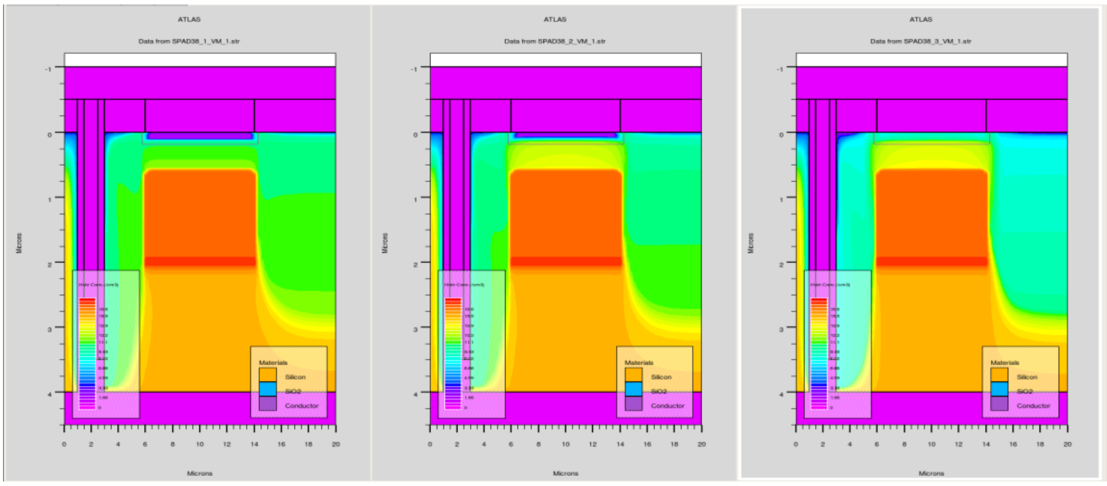



Fig. 9: Hole concentration. Notice the high hole concentration at junction in the right two figures. These undergo Breakdown.

# 3. Electrical Properties Measured

## 3.1. Electric Field and flow of charge carriers

The most important factor for controlling the flow of electrons is electric field. In the reverse breakdown region, the current is due to excess charge carriers generated in the depletion region. From The junction, electrons move towards the positively charged electrode at the top whereas, the holes move towards the bottom negatively charged electrode. Thus, a current is established. As you can see in fig 10(a) there is an electric potential gradient at the sides of the p-n junction. However, the potential is very much uniform at the centre, below the junction. As a result, the minority electrons are not deflected by any electric field and move straight into the junction.

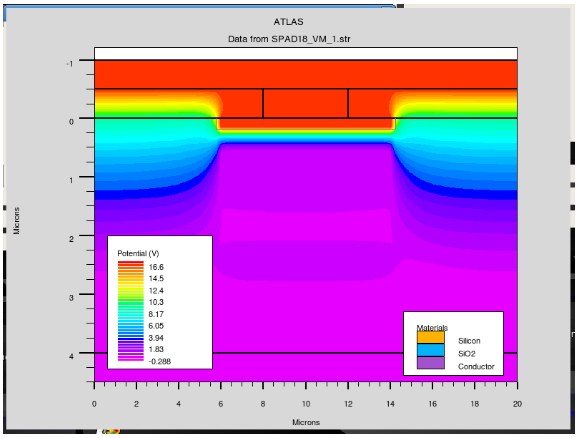
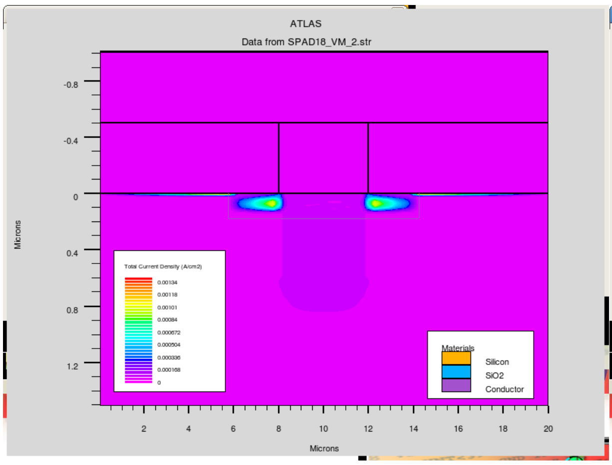



Fig. 10(a) : Potential Distribution

If after introduction of TSV the electric field under the junction doesn't change much, the breakdown characteristics won't change.

The same exercise was performed by reversing the nature of dopings, i.e the now n-type regions were doped p and now p regions were doped n. Also, care was taken to reverse polarity of electrodes to ensure reverse bias. Similar results were obtained.



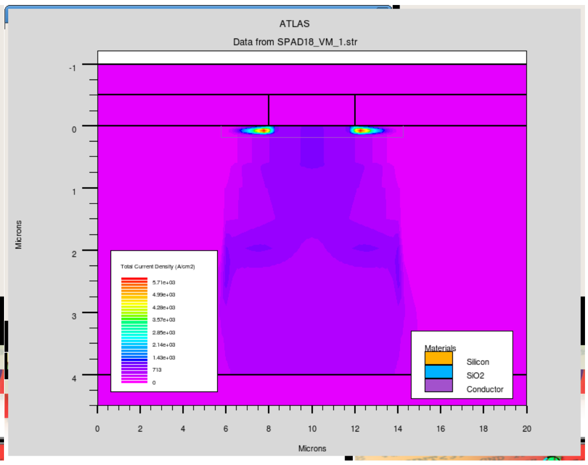




Fig 10(b) : Current Density before breakdown

Fig. 10(c): Current Density at breakdown

Both are not on the same scale

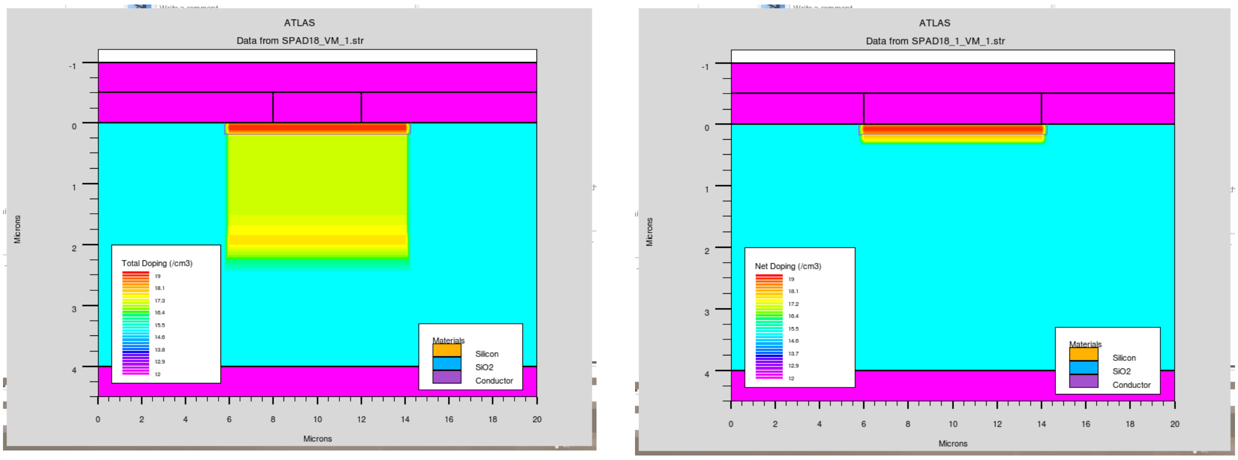



Fig. 11(a): Deep Doping

Fig. 11(b): Shallow Doping

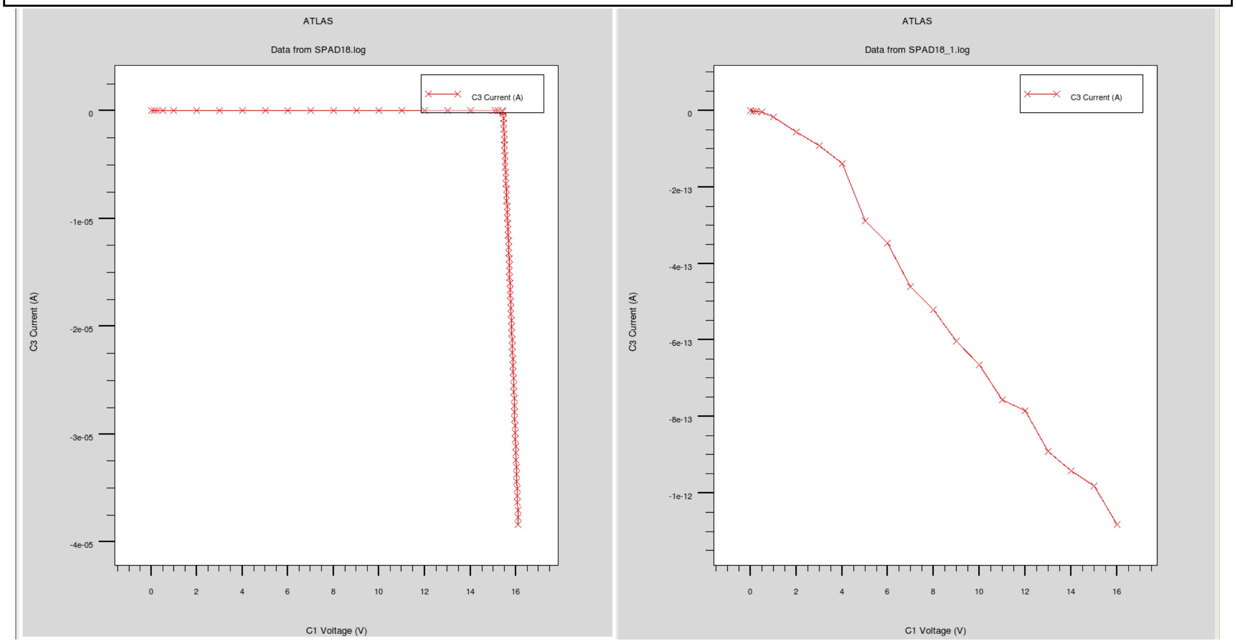



Fig 12 I-V Characteristics of the two cases.

A leakage current of the order of $10^{-12}$ to $10^{-14}$ amperes per micron (per micron of depth of 2D cross section along the third axis) flows through the electrodes before breakdown. This leakage current is purely resistive in nature and is primarily due to flow of electrons from the sides of $SiO_2$ insulation between the electrode and conductor. My simulations confirm a breakdown current of atleast $10^{-5}$ ampere per micron ,which dominates over the other leakage currents in the current density plot 10(c).

### 3.2. Resistance

Once the electrons and holes are created at the depletion region, they need to travel to the respective electrodes. For this there is a need for a low resistance path from the junction to the electrodes. The importance of this fact is illustrated as we compare the two structures shown in fig 11.

**3.2.1.** The two structures shown in fig 11 differ only in the depth of p doping. Though both have a junction at the same depth(~0.02 microns), 11(a) has a much deeper p+doping (~2 microns) than 11(b).

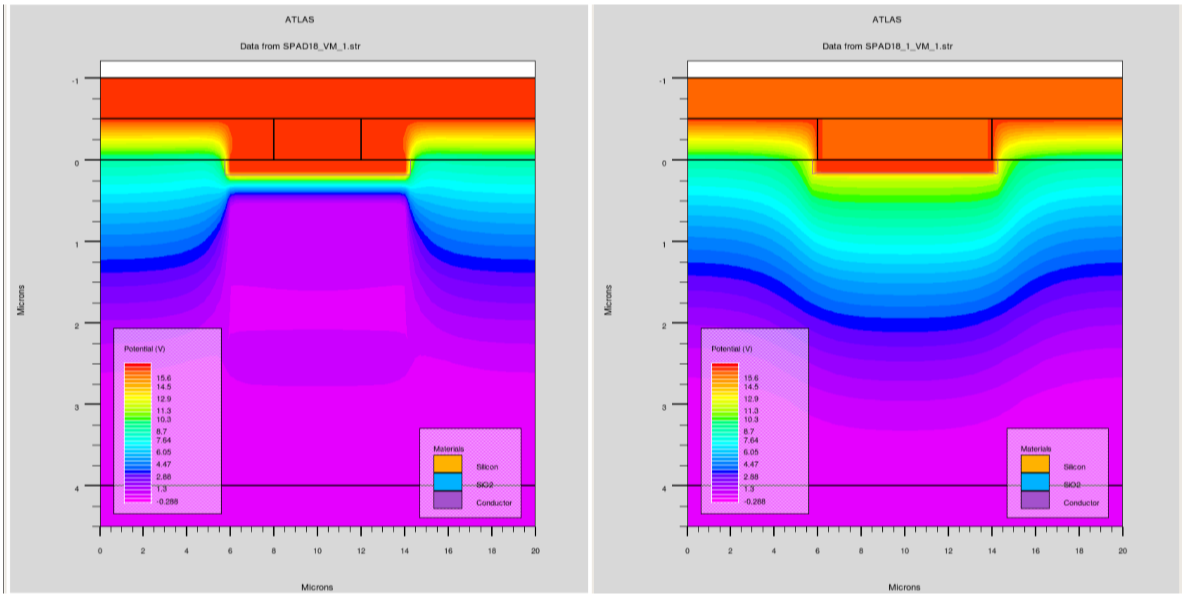



Fig. 13 (a): Potential Distribution

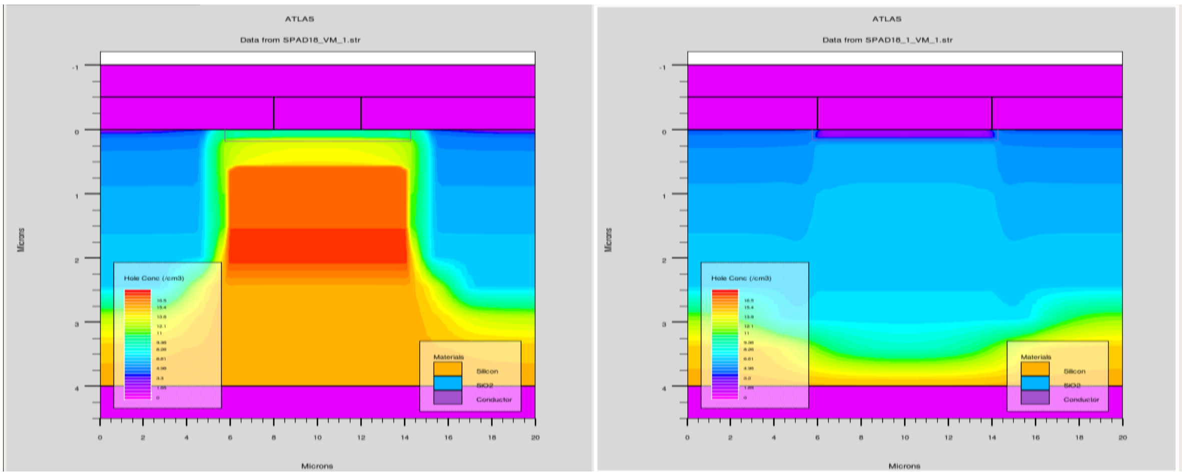



Fig. 13 (b): Hole Concentration.

## 3.3. Probability of Avalanche

Probability of avalanche as the name suggests, represents the tendency of a charge carrier to cause avalanche. The cumulative effect of individual probabilities of avalanche could be switching (on/off) of the key in fig.3. However the way Silvaco relates probabilities of individual carriers to the switching on/off of the circuit is not understood very well by me.

The calculation of probability in Geiger model of Silvaco is based on the following two equations. The numerical method adopted to solve these differential equations has been talked about in Ref[4]. Though Silvaco doesn't explicitly mention, but reading the Silvaco documentation on Geiger [3] and the associated paper[4], it seems that an iterative process is used to solve these differential equations. However I could not figure out exactly on what parameters should the probability of avalanche depend.

$$\frac{dP_e}{ds} = (1 - P_e)\,\alpha_e P_p$$
$$\frac{dP_h}{ds} = (1 - P_h)\,\alpha_h P_p$$
$$P_p = P_e + P_h - P_e{*}P_h$$

Here $P_p$, $P_e$ & $P_h$ refer to pair, electron and hole probabilities of avalanche and $\alpha_e$ and $\alpha_h$ are electron and hole ionization co-efficients.

Despite of my failure to do so, through my simulations I observe a relation between the X direction electric field and probability of avalanche and can also come up with an explanation. To illustrate this, I use two examples in each of which I have compared two different structures.

**3.3.1.** Here two structures, one with a TSV (fig. 14(a)) and the other without a TSV (fig. 14(b)) are compared. Fig 14 (c) and (d) show the probability of avalache and 14 (e) and (f) show the electric field in X direction. If the four region of probability of avalanche is named R1, R2, R3 & R4, they follow the following pattern.

| Sr.No | Electric Field Direction | Electric Field Magnitude (V/cm) | Probability of Avalanche |
|---|---|---|---|
| R1 | Towards Center | 85,000 | 0.00475 |
| R2 | Away from center | 75,000 | 0.00575 |
| R3 | Towards Center | 70,000 | 0.0055 |
| R4 | Away from center | 70,000 | 0.0055 |

If the corners of the doped regions have a high electric field inwards, they facilitate the flow of electrons away from the central region and thus make them unavailable for avalanche. Thus the regions having high inward electric field will divert more electrons and as a result have a low probability of avalanche.

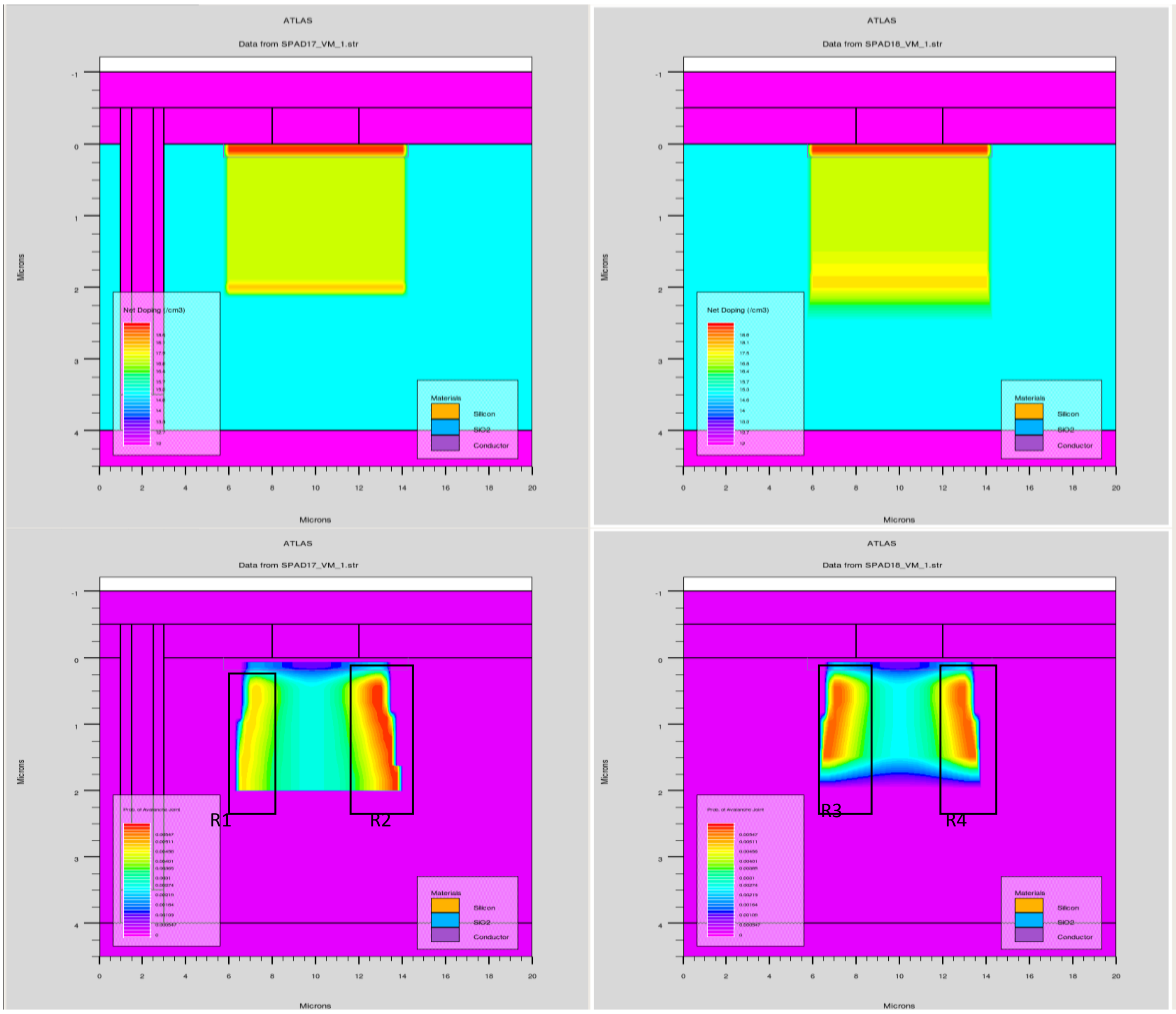



Fig. 14 (a), (b), (c) & (d) : The TSV introduces an X direction electric field that diverts electrons away from the central doping region towards the left side. This leads to decrease in probability of avalanche.

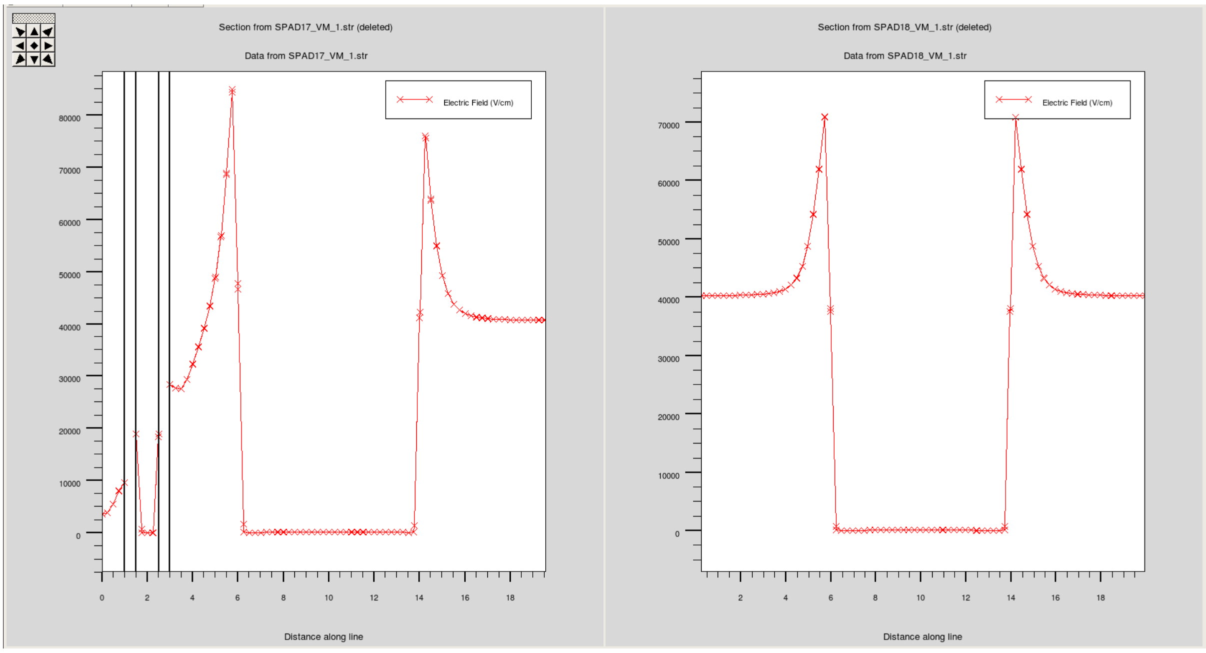



Fig. 14 (e) & (f) respectively : X direction Electric Field in the two cases 14(a) and 14 (b).

**3.3.2.** Here the comparison is between the two structures shown in 15. 15(a) has a doping that extends upto the TSV, whereas the doping in 15(b) stops at a distance of 3 microns before the TSV. The probability of avalanche is depicted in 15(c) and 15(d). Electric field in 15 (e) and (f).

Here though the X electric field plays some role, the fact that electrons cannot escape from one of the side, leads to an increase in probability of avalanche. This is evident in figure 15 (c) and (d).

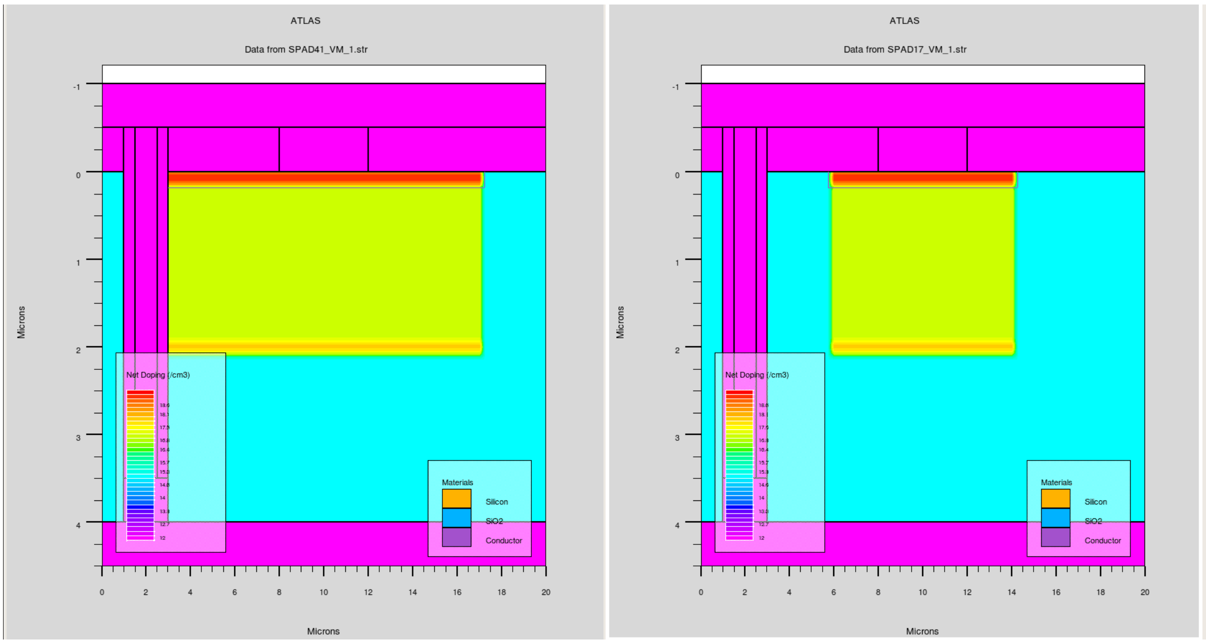
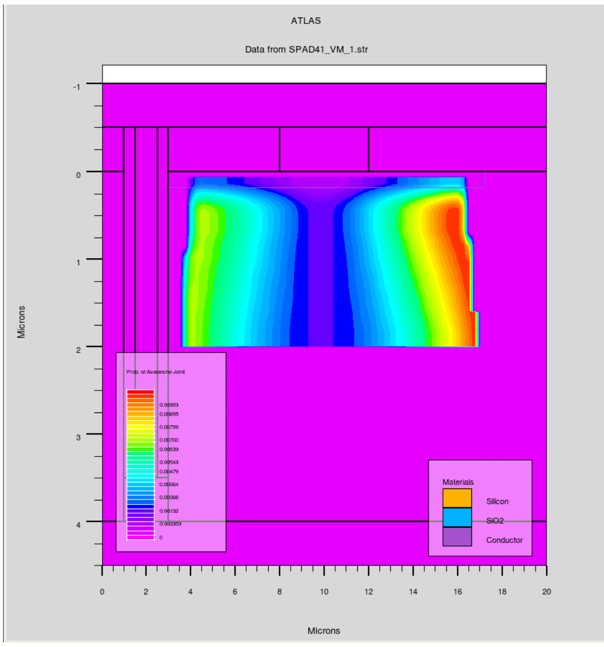



Fig. 15 (a) : Doping extends upto the TSV

Fig15(b) : limited width of doping



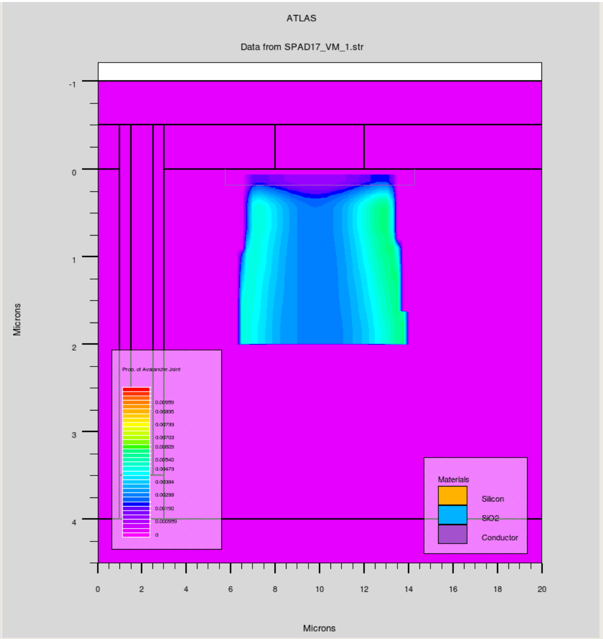
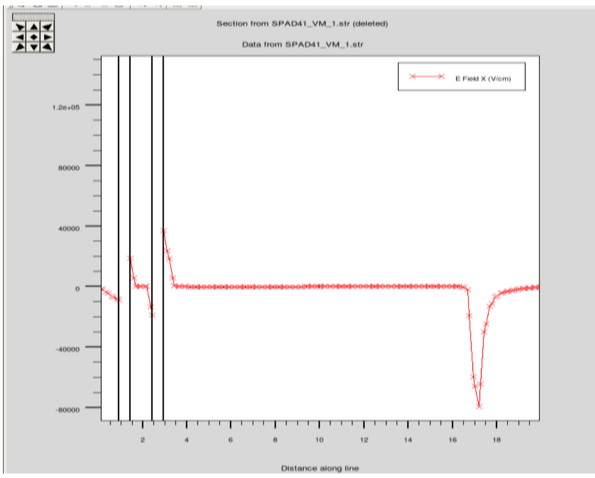




Fig. 15(c): POA in 15 (a)

Fig 15(d): POA in 15(b)



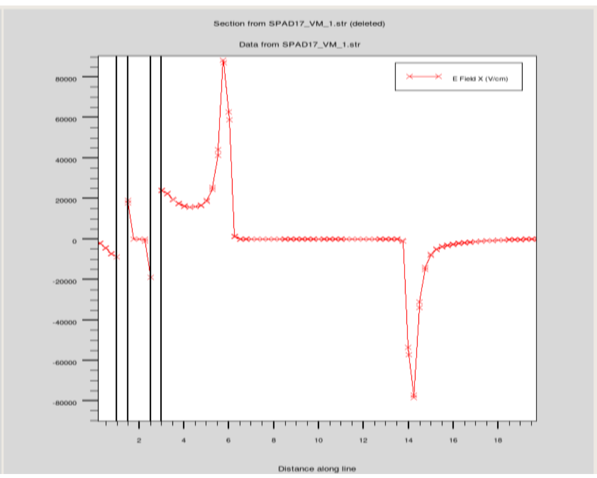
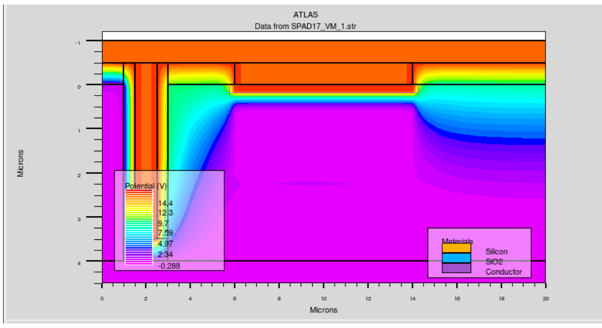




Fig 15(e): X direction electric field in 15(a)

Fig 15(f): X direction electric field in 15(b)

# 4. Insertion of TSV

After this analysis, I compare two similar SiPM structure, one of which has a TSV inserted (fig. 16(a)) and the other is a simple diode (fig. 16(b)).The most important is the potential distribution pattern that governs flow of charge carriers. The potential pattern shows some variation on the sides, as insertion of TSV extends the high potential region from the top electrode. However, there is no change in the central region below the junction. As a result most of the characteristics of the SiPM do not change even after the insertion of TSV.



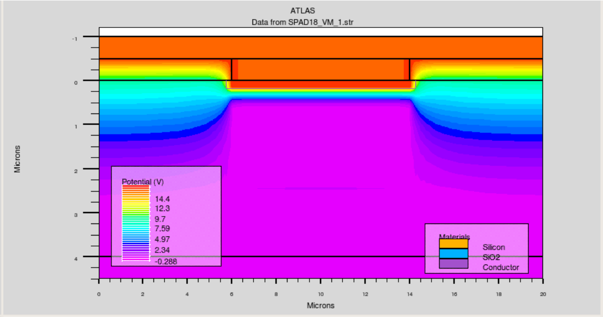
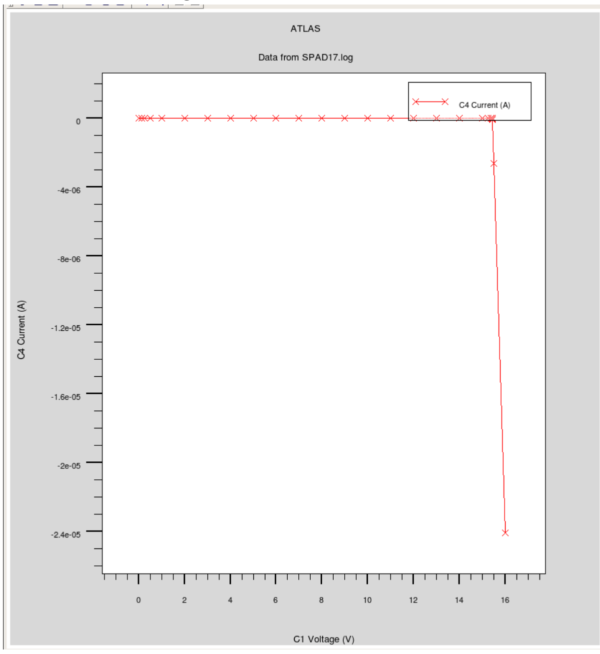




Fig16(a) : Potential Distribution with TSV
Fig16(b) : Potential Distribution without TSV

The table below gives an idea of the changes that one observes after insertion of TSV.

| Characteristic | Changed / Same | Figure |
|---|---|---|
| Potential | Changed on sides but the same below junction | 16 (a)& (b) |
| Leakage current | Same | 16 (e) & (f) |
| Breakdown Voltage | Same | 16 (c) & (d) |
| Current Density Pattern | Slightly Changed. Hole current is now slightly away from TSV. | 16 (g)-(j) |
| Y direction Electric Field | Same | 16 (k) |
| X Direction Electric Field | Changed | 16(k) |
| Probability of Avalanche | Changed (see section 3.3.1.) | 14 (c) & (d) |

## 4.1. Breakdown Voltage



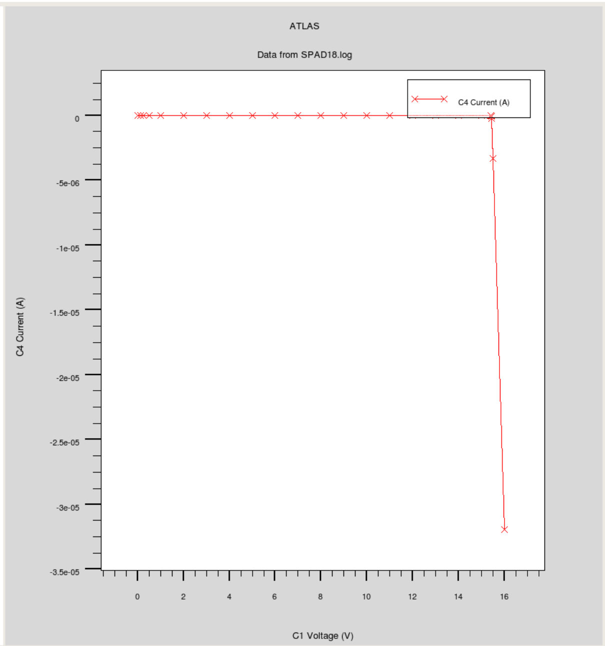
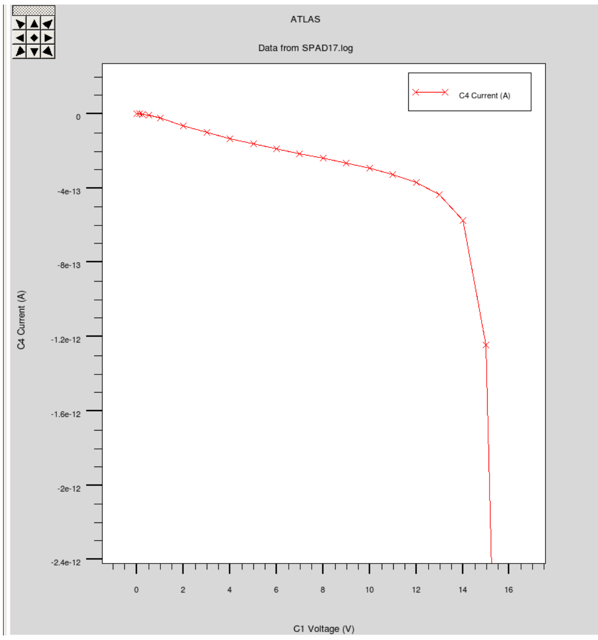




Fig. 16(c): I-V Characteristics in 16(a)
Fig 16(d): I-V Characteristics in 16(a)

## 4.2. Leakage current



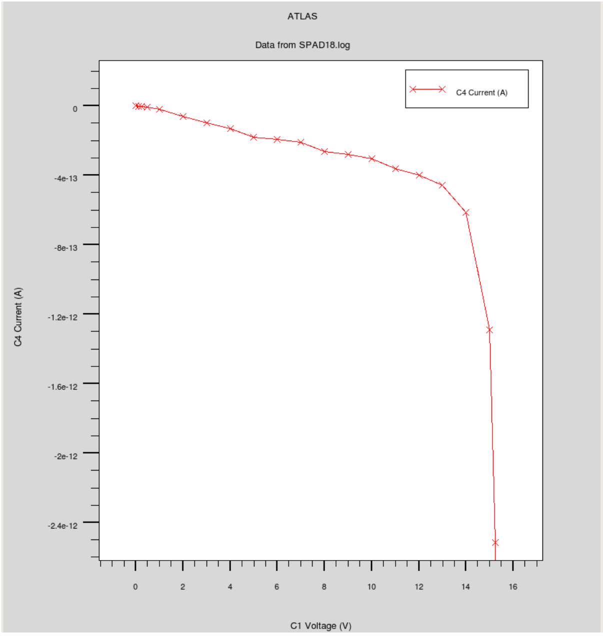
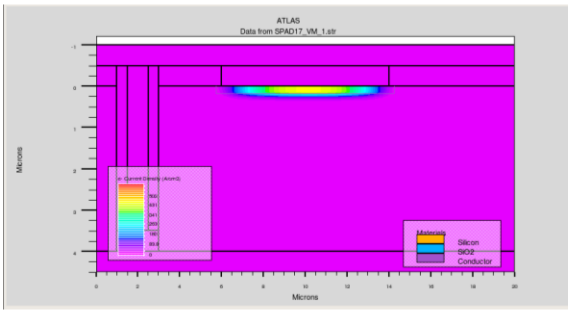




Fig 16(e) : Leakage Current in 16 (a)

Fig 16(f) : Leakage Current in 16 (b)

## 4.3. Current Density pattern



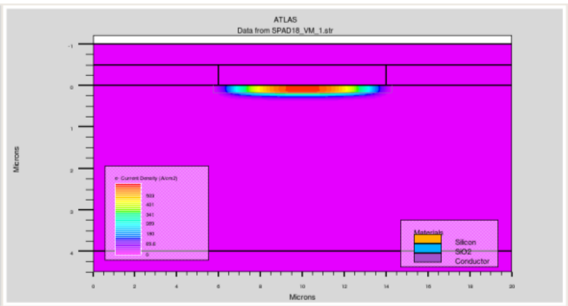
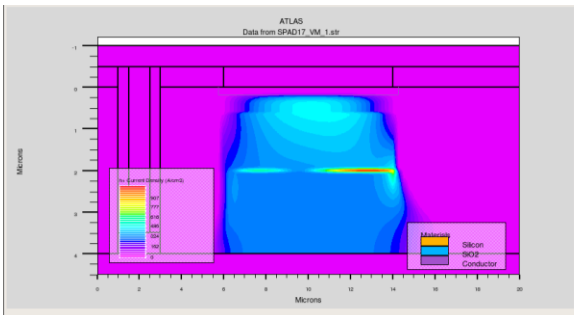




Fig. 16(g): Electron Current Density in 16 (a)

Fig 16(h): Electron Current Density in 16 (b)



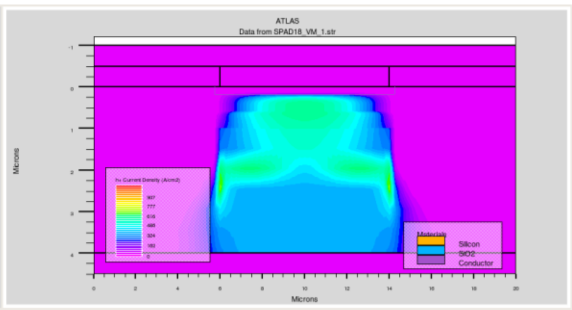




Fig 16(i) : Hole Current Density in 16 (a)

Fig 16(j) : Hole Current Density in 16 (b)

### 4.4. Y and X Direction Electric Field

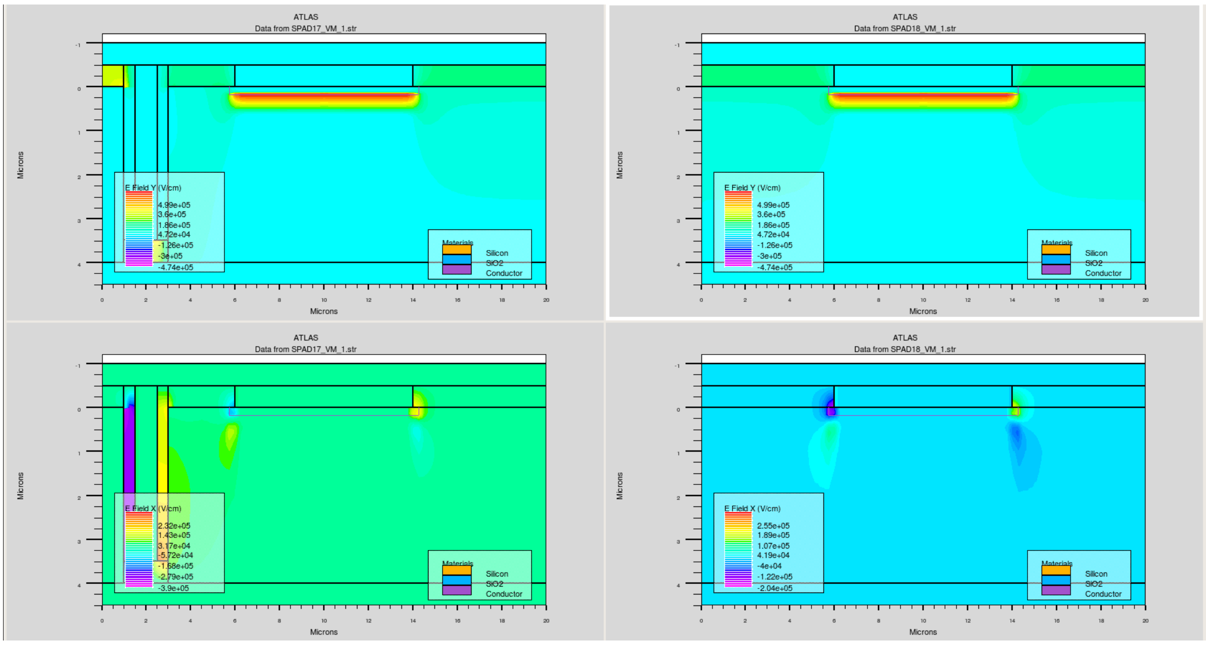



Fig 16(k) : The top two are Y-electric field contour plots and the ones at the bottom are X-Direction Contour plots.

## 5. 3D Simulations

After performing the above 2D simulations, I performed 3D simulations. The prepared structure is the cubical structure shown in figure 4. The breakdown voltage I obtained is close to 13 volts. Below fig 17 shows the I-V characteristics of cubical SiPM structure.

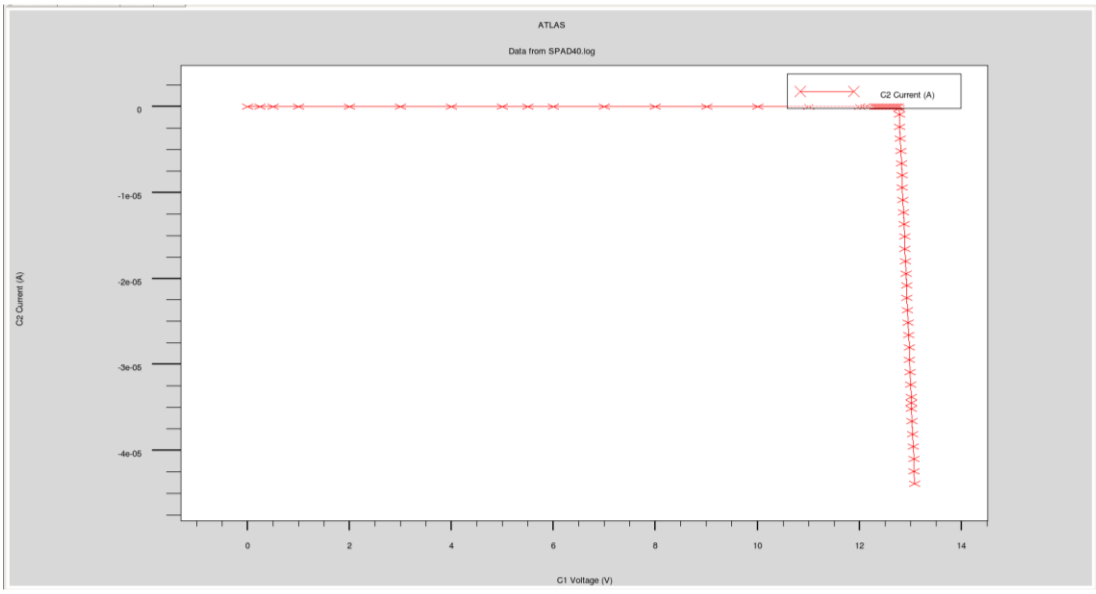



Fig. 17 : 3D I-V curve

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