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On biasing the silicon microstrip detector with wide strip pitch

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Abstract

We observed deteriorated IV curves when ATLAS SCT silicon microstrip detector was biased for a long period. The leakage current is nearly halved at voltages below V_k where the detector was kept biased. At these voltages, the noise figure is deteriorated and signal charge is spread across the neighboring strip. The detector performance is, however, not degraded at V_k or above. This problem disappears by setting off the bias voltage but it requires a certain time which is dependent on the temperature. We characterized the phenomena in detail and propose to inhibit specific biasing scheme in the experiment.

Key words: silicon; microstrip; ATLAS; SCT; IV; instability
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1 Introduction

Large scale silicon microstrip detectors are instrumented in various particle physics experiments for their excellent spatial resolution, fast response and resistivity against radiation. For example at the LHC, the ATLAS Semiconductor Tracker (SCT) [1] covers the region outside the PIXEL detector to perform precision tracking inside a 2 T magnetic field together with straw-type proportional tubes, Transition Radiation Tracker, located outside the SCT. The SCT consists of four concentric barrel layers composed of 2112 modules, and nine layers each side of the endcap composed of 1976 modules.

All the barrel detector modules have been constructed at four qualified sites, including our Japanese site, where intensive quality assurance measurements were performed in an agreed program. In the course of testing we eventually detected a noticeable increase in the noise figure which was evaluated using test pulses implemented in the readout ASIC chips.

The investigation is extended to identify and understand this phenomenon, reaching a conclusion that the detector performance is deteriorated when the bias is lowered after keeping high the bias voltage for a long period. The deterioration is essentially a degradation in interstrip cross-talk. This recovers by itself according to the new bias voltage, but it requires days to weeks especially when the environment temperature is low.

We describe the properties of deteriorated IV curves of ATLS SCT modules in Sec. 2. The influence to the detector performance is given in Sec. 3 in terms of electrical noise and charge collection evaluated using Nd:YAG laser. The characteristics, magnitude of deterioration and transition time are evaluated at different temperatures, which are given in Sec. 4.

2 Observation of deteriorated IV curves

All the barrel sensors were fabricated by Hamamatsu Photonics (HPK) using 4" process technology. There are 768 readout strips per sensor at a pitch of 80 μm. The p^+ implant electrodes 16 μm wide and 63 mm long are biased through poly-silicon resistors of 1.5 MΩ. The readout Al electrodes 22 μm wide are AC coupled to the implant strips via SiO_2 and Si_3N_4 layers. Four identical silicon microstrip sensors are glued back to back sustaining a stereo angle of 40 mrad to construct a detector module.

Figure 1 shows the IV curves measured every 4 h while the bias was kept at V_k=350 V when the voltage was not scanned. The voltage was scanned up to 500 V throughout this study unless otherwise noted. The temperature was 40°C. The general feature is that the leak current increases in the first scans, then the current at lower voltage region starts to decrease, reaching the asymptotic IV curve shape which has two plateaus one below V_k and another above V_k. The full depletion voltages are around 80 V, therefore the second plateau is not determined by the full depletion voltage but by the voltage kept. Similar deteriorated IV curves were observed for other modules, independent to the atomsphere, air or nitrogen.

Since the sensor prototyping, we have recognized that HPK sensors exhibit a monotonically increasing IV curve at first measurements, which turns to an expected IV shape after some scans showing a clear shoulder corresponding to the full depletion voltage. This observation is present in Fig. 1 as the difference between the scans labeled "1" and "2". Similar observation is reported in

Ref. [2] for HPK large area strip sensors. They report a similar IV curve when measured with a ramping rate of 10 V/s. They also find that the curve becomes as expected when the ramping of 1 V/m is chosen.

The transitions following the scan “2”, though, are not expected from micro-discharge or from conventional surface-charge effects. The transition takes much longer at lower temperatures, as described in detail in Sec. 4, therefore the deterioration has escaped from detection at 15°C where we performed the 24 h stability test on the SCT modules as a part of the quality assurance program.

The dependence of the second plateau on V_k is evident in Fig. 2, where V_k was set to 150 V and IV measurements were repeated every 4 h at 40°C. The IV curves are deteriorated in the voltage region below 140 V. For the SCT modules with full depletion voltages of around 80 V, 150 V bias is a realistic operation condition. Hence the present observation directly affects the detector performance if we need to lower the bias after a long time of detector operation.

Figure 3 shows the IV transition after the time when V_k was lowered to 150 V. The sample had been biased at 350 V, showing at time zero the deteriorated IV curve similar to the asymptotic curve shown in Fig. 1, labeled “12”. The second plateau voltage decreased gradually from 340 V to 140 V in about 40 h at 40°C. We note that the asymptotic IV curve at 150 V is deteriorated similar to the asymptotic curve in Fig. 2 “13”, without showing a shoulder corresponding to the full depletion voltage.

Similarly, when the bias was set zero from 350 V, the curve transited as shown in Fig. 4. The asymptotic IV curve, obtained after typically 80 h, is similar to, but not exactly the same as, the one labeled “2” in Fig. 1.

The maximum voltage 500 V in the IV scan was lowered for some samples, but the general observation remained the same. This excludes the possibility that 500 V might be too high for stable operation.

3 Detector performance at deteriorated conditions

As described before, we first noticed the degradation from some increase in the noise figure. In a module, a total of 1536 12 cm long strips are wirebonded to 12 ABCD3T[3] chips. The ABCD3T chip is a binary readout ASIC, composed mainly of amplifier-shaper and discriminator stages, followed by digital pipeline and output buffer stages. The DACs implemented in the chip perform the gain calibration by scanning the discriminator levels against variable input test charges. The noise figure, equivalent input noise charge, is calculated at 1 fC input charge from the spread of the discrimination curve normalized by the chip gain.

The required noise figure is less than 1500 ENC so that a 1 fC threshold can be applied with negligible noise contributions, at a level of 5×10^{-4} or less. The average and rms spread of 1536 readout channels are listed in Table 1. The values at 150 and 350 V biases are given for the module operated at V_k=350 V and at 40°C environment. At 350 V, the first measurement at time zero resulted that the noise was slightly larger than the requirement, but it soon decreased to a 1400 level. Since the noise level decreases with temperature, 5 ENC/degree [3], both results are acceptable at about −10°C environment where modules will be operated. The value at 150 V, however, increased with time, reaching a 1750 level. The increase seems to be correlated with the magnitude of deterioration (see Fig. 1). Note that 150 V is well above the full depletion voltage.

In order to evaluate the charge collection, collimated Nd:YAG laser was injected to the same module. The used Q-switched laser with 1064 nm wavelength can simulate passage of charge particles, as the details of the apparatus are described in [7]. The laser was collimated to 2×2 μm and injected right next to the strip number 381, one of the strips at the module center. The collected charge was measured together with of neighboring strips. The result is shown in Fig. 6. Before the deterioration, the charge is collected by essentially strip number 381 with negligible cross-talks to the neighbors. After the IV curve reached the asymptotic shape with V_k=350 V, the charge collection is degraded in the voltage region below 300 V, showing a substantial cross-talk to strip number 382: the laser was spotted between strip 381 and 382. The charge sum of 380 to 382, though, shows the curve similar to the one measured at time zero. This ensures that the detector is fully depleted in the deteriorated voltage region. We also notice that the cross-talk to strip number 380 is not enhanced. This implies that the cross talk is not through capacitive coupling but the electric field is somehow disturbed so that some fraction of charge is induced directly to the neighbor.

Simliar deterioration was observed also when the laser was spotted to the strip closest to the side, indicating the effect should present in the entire detector region.

4 Characteristics of IV deterioration

The study described in the previous section leads to a conclusion that noticeable performance degradation is inhere associated to the deterioration of the

IV curve but the performance should not be affected in the bias region at and above V_k. There is even a margin of 50 V judging from the charge collection curves. In the detector operation point of view, the detector should perform as expected as far as the bias is not lowered. Should the bias is lowered after a long time operation, we must wait for the detector to recover from the deterioration. The magnitude of the deterioration and the time constants are investigated.

The deterioration is observed in single sensor where the bias was provided to the bias ring and backside. The difference to the module is that the aluminum strip voltage is floating in single sensor. The evolution of IV curves measured for single sensor is shown in Fig. 5, where the measurements for other sensor types, CDF Run2B[4] and CDF SVX L00[5], are compared. The main sensor parameters are summarized in Table 2. All the sensors are p^+-on-n microstrips fabricated by HPK. The deterioration of IV curves is visible in other sensors, but the magnitude and separation between the second plateau voltage and keep voltage V_k are different. The tendency is that if the strip pitch is larger, the magnitude is larger and the voltage margin is smaller.

For quantitative discussion, we extracted characteristic parameters from the measured IV curves. In Fig. 7 we plot the leak currents at a given voltage V_t (320 V in this case) against time. The current values are normalized by the value above V_k (350 V in this case). The transition can be fitted to a functional form to derive A_r the asymptotic decrease in magnitude of the normalized current, T_0 the time for the normalized current to decrease by $A_r/2$, T_s one sigma spread of the transition time. The fit results are given in the plot as an example. Among these, A_r and T_s can be extracted reliablly, about 10% uncertainty evaluated from repeated measurements, while T_0 depends on the voltage V_t and initial conditions whether the detector was previously biased or not due to the effect described before for the difference of "1" and "2" in Fig. 1. Roughly speaking T_0 is 3–5 times T_s, and the current reaches the asymptotic value in a time scale 5–7 times T_s.

Using the data shown in Fig. 5, the fit resulted that the largest decrease A_r near V_k is 14% for SVX2B and negligible for L00 sensors. Two SCT modules with <111> and <100> orientation showed decreases of 51% and 61%, respectively. One SCT sensor with <100> showed a decrease of 58%. The magnitudes of deterioration are similar between SCT module and sensor, which are about four times larger than SVX2B. Since the ratio of the strip pitches is roughly two, the magnitude is about twice the ratio of strip pitches. There is a tendency that the sensors with <100> are influenced more than those with <111>.

Figure 8 shows the T_s measured at different temperatures from 5 to 70°C. The temperature dependence can be well fitted to an exponential, resulting

$T_s = A \exp(-\alpha T)$ with $A \approx 20$ h and $\alpha = 0.030 - 0.032$

where T is the temperature in Centigrate. As described before the total time to reach the asymptotic shape requires 5–7 times this value: 4–6 days at 0°C and 6–8 days at −10°C. Although no systematic study was made on the recovery times, they should be similar to the time scales described here since the time scales about 30 h in Fig. 1 and about 40 h in Fig. 3 are not much dfferent.

The voltage where the second plateau is reached is plotted in Fig. 9 as a function of temperature. The voltage decreases at lower temperature, providing a wider voltage mergin in view of stable operation.

The magnitude of deterioration A_r is found to exhibit weak dependence on the temperature.

5 Interpretation of the deterioration mechanism

The long characteristic time constant which is temperature dependent may be related to slow movement of ions trapped in the oxide layer and at the boundary. Figure 10 shows the field strength around the strip when the backplane was biased to 350 V, evaluated using a TCAD[8] program. Owing to the design that the Al readout strip extends over the implant strip, the maximum field locates inside the oxide layer, where we calculated the maximum to be 1.3×10^6 V/cm. The actual value should differ due to inaccurate modeling of detector processing, but also due to accumulation of charges that should act to moderate the field strength. As many field lines are gathered inside SiO_2, holes traveling to the p^+ implant will be blocked at the boundary. After having operated for long time, the holes at the boundary should block the movement of ions in the oxide, and electrons attracted by the ions will be accumulated at the boundary, reaching equilibrium in densities. The equilibrium densities are high with the electric field, namely V_k.

Once the bias is lowered, the maximum field is reduced to 0.9×10^6 V/cm at 150 V, and a part of the electrons which have been accumulated are first allowed to access to the electrodes. The data shown in Fig. 3 indicate that 1 μA initial current increased to 3 μA over 40 h of period. Taking the sensor area into account, this corresponds to roughly 1×10^{17} electrons/cm^2 are released to the implant by the voltage shift from 350 to 150 V. When the movement of slow ions are stabilized, hence the electrons are again attached to the ions, the IV is also stabilized.

Some efforts have been made to quickly recover from the deterioration, including UV illumination on the surface and forward-biasing for short time. Both turned out not to be effective, as explained if the problem is due to slow ions.

6 Summary

We have observed unexpected deterioration in the IV curve when lowering the detector bias after having kept the detector bias for long time. In such deteriorated IV region, the charge collection and noise figure are degraded. The deterioration recovers by itself, but this requires days especially in low temperature environment.

Since the detector performance is not degraded at and above the voltage where the detector has been biased for long time, the characteristics have to be taken into accounton when the detector bias is lowered.

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Table 1
Average and one rms spread of the noise figures at 150 and 350 V, measured at different time since biasing at V_k=350 V. The numbers "1" and "4" correspond to those in Fig. 1 and "asympt" is when the IV curve is stabilized.

	150 V		350 V	
	average	rms	average	rms
T=0 ("1")	1452	72	1524	77
T=12h ("4")	1658	93	1395	72
T=40h (asympt)	1753	84	1397	67

Table 2
Main parameters of tested microstrip sensors. Run2B and L00 sensors are implemented with intermediate strip.

	ATLAS SCT	CDF Run2B	CDF LOO
strip pitch (μm)	80	37.5	25
readout pitch (μm)	80	75	50
imlant width (μm)	16	8	5
Al width (μm)	22	14	7
area (cm×cm)	6.4 × 6.4	3.9×9.4	0.8 ×8.6
HPK process	4"	6"	4"
wafer orientation	<111> and <100>	<100>	<111>

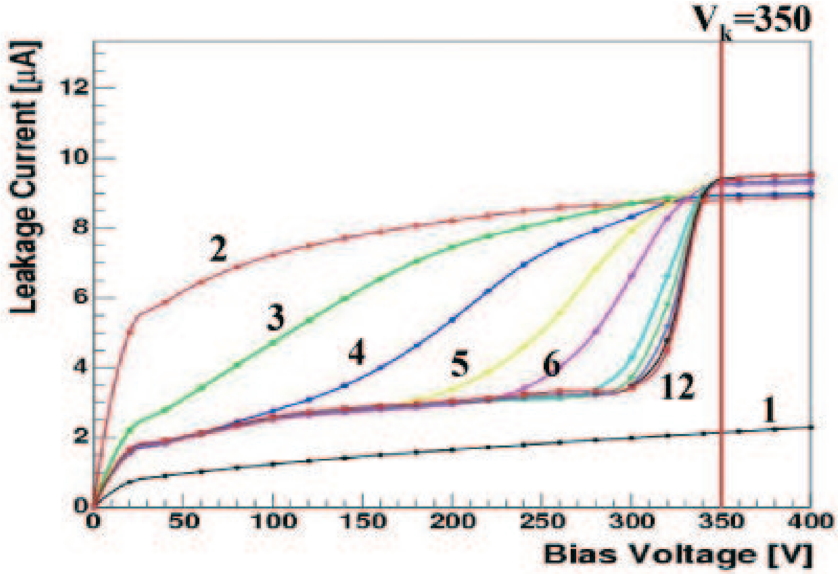

Fig. 1. IV curves of an SCT module measured every four hours. The sequence is indicated by the numbers attached to the curves. The temperature is 40°. V_k, bias kept between the IV measurement, is 350 V.

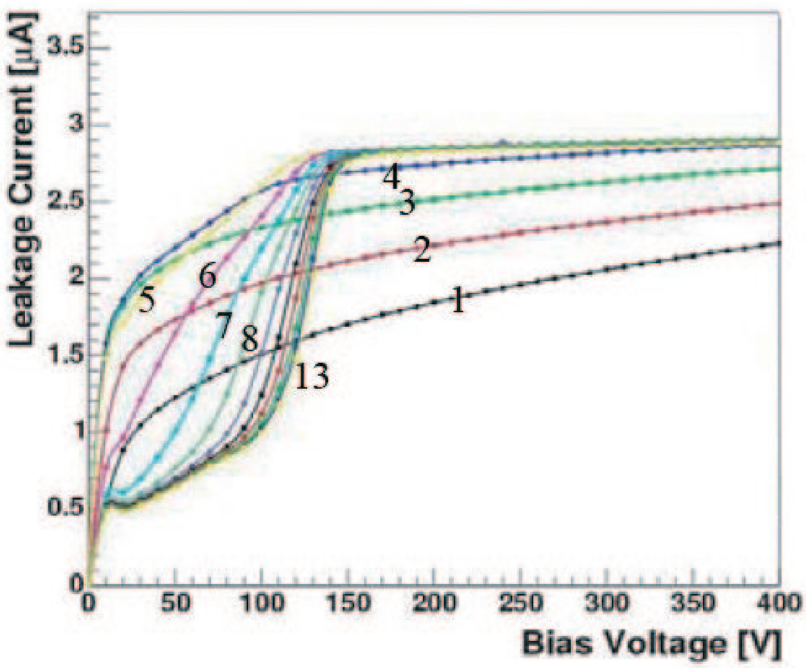

Fig. 2. IV curves of an SCT module measured every four hours for V_k = 150 V. The sequence is indicated by the numbers attached to the curves. The temperature is 40°.

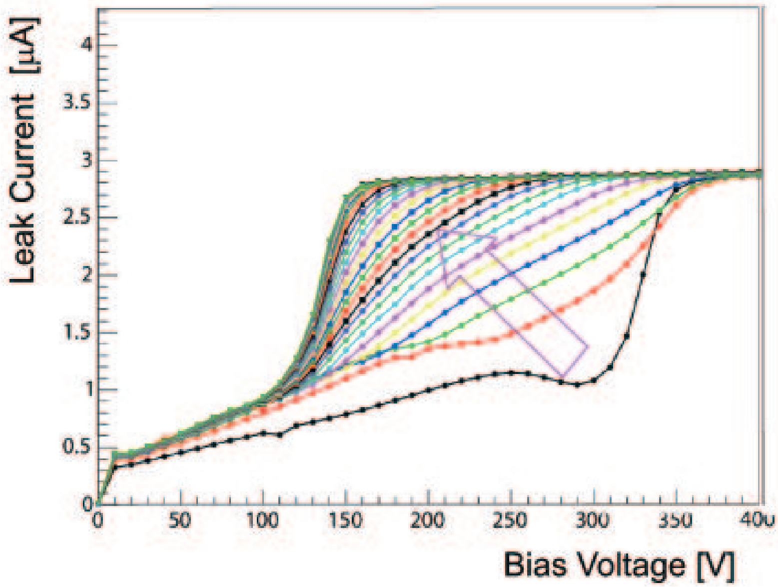

Fig. 3. IV curves of the same module of Fig. 1, measured every two hours at temperature of 40°. The time zero is when V_k was lowered from 350 V to 150 V after the IV curve had been stabilized at V_k= 350 V. The curves changed in the sequence indicated by the open arrow.

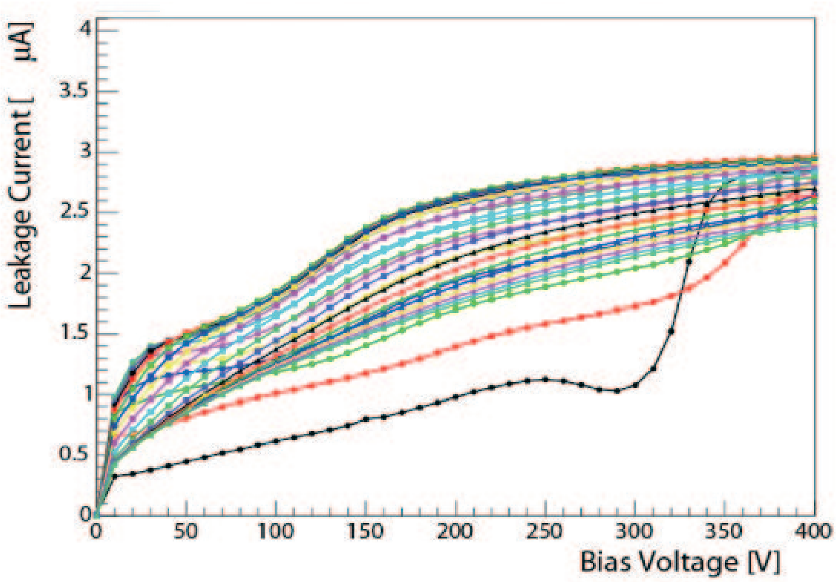

Fig. 4. IV curves of the same module of Fig. 1, measured every two hours at temperature of 40°. The time zero is when V_k was lowered from 350 V to 0 V after the IV curve was stabilized at V_k= 350 V.

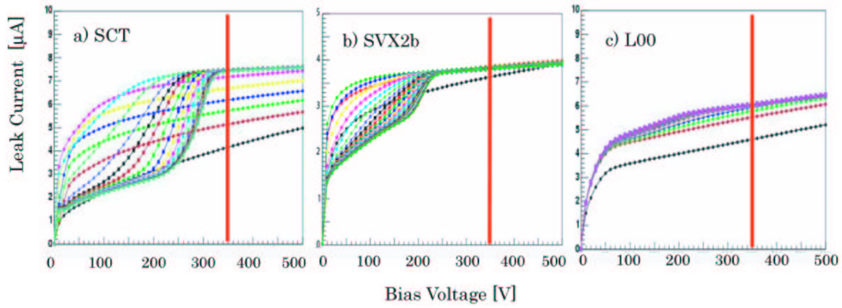

Fig. 5. IV curve transitions compared among a) SCT, b) CDF SVX2B, and c) CDF SVX L00 sensors. The measurements were every 2 h at 40° temperature with V_k= 350 V indicated by vertical lines. Transition sqeuences are similar for a) and b), gradual increases followed by decreases in lower bias voltage region. Though the magnitude of the decrease is tiny for c), the general sequence agrees with a) and b).

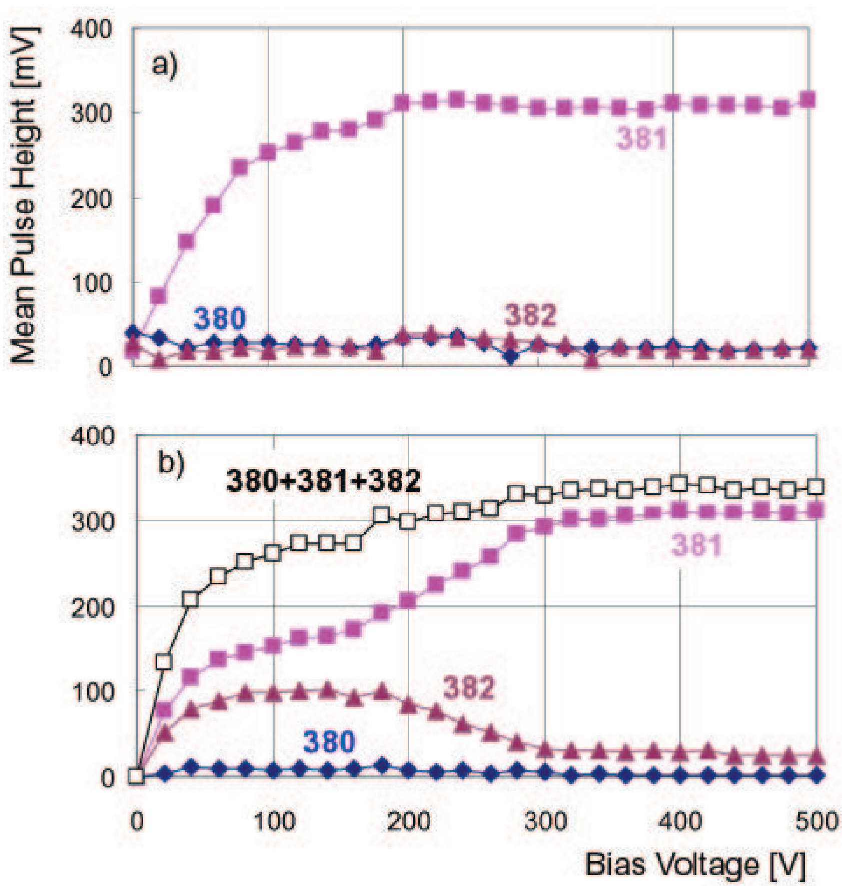

Fig. 6. Charge collection as a function of bias voltage for the same SCT module but a) before and b) after the IV curve is deteriorated. The laser was spotted between strips 381 and 382 but close to strip 381. The collected charge is shown separately for strips 380 to 382 with the sum for b).

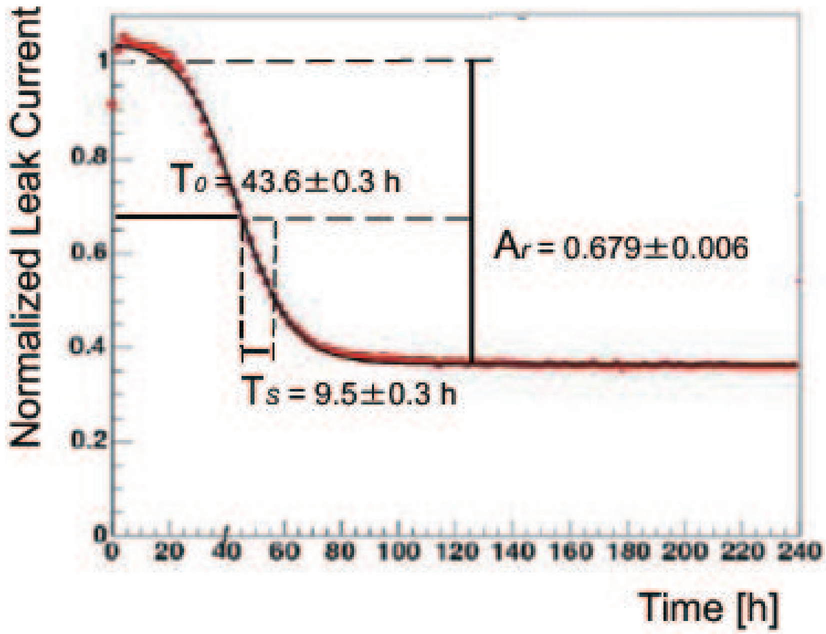

Fig. 7. The leak currents at 320 V are plotted as a function of time for V_k=250 V.

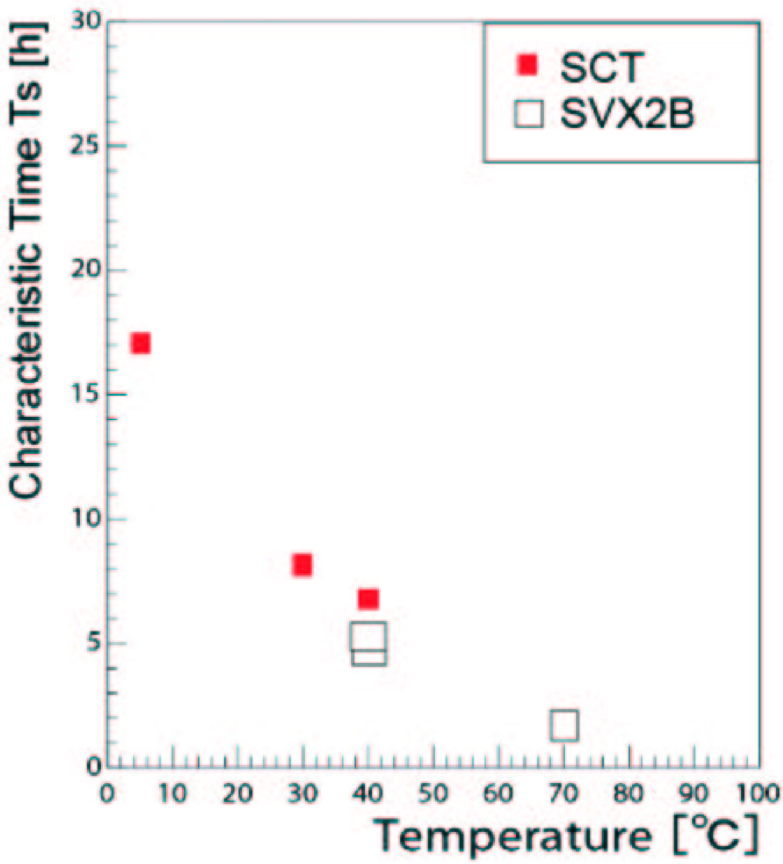

Fig. 8. Characteristic time spread of deterioration transition as a function of the temperature.

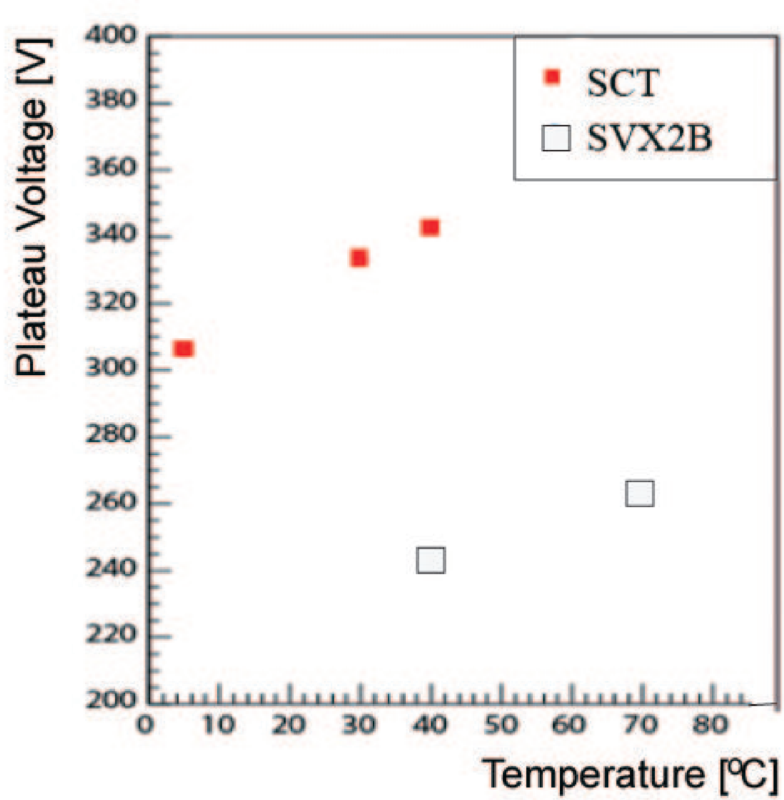

Fig. 9. The voltage where the second plateau is achieved, shown as a function of temperature. The detector is biased at $V_k = 350$ V.

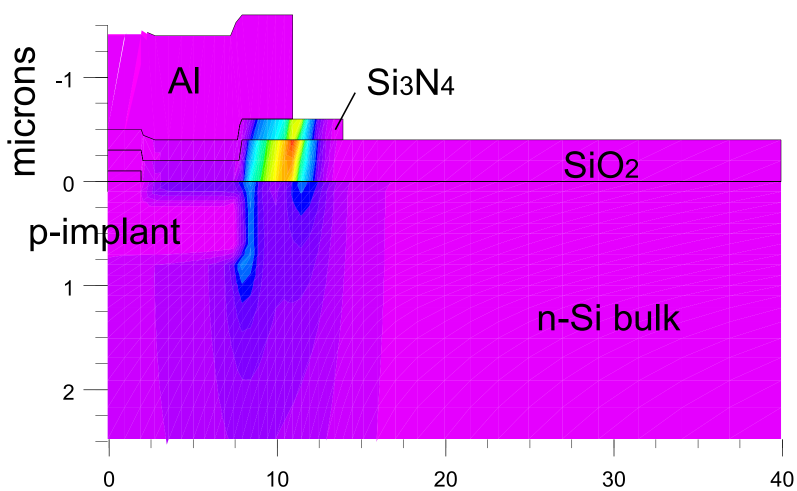

Fig. 10. Simulated electric field distribution around the strip. The field is maximum at the brightest region located inside SiO_2.