Temperature dependence of the response of ultra fast silicon detectors

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Temperature dependence of the response of Ultra Fast Silicon Detectors

R. Mulargia[a,b,1] **R. Arcidiacono**[b,e] **A. Bellora**[a] **M. Boscardin**[c,d] **N. Cartiglia**[b] **F. Cenna**[a,b] **R. Cirio**[a,b] **G.F. Dalla Betta**[g,d] **S. Durando**[a] **A. Fadavi**[b,f] **M. Ferrero**[b] **Z. Galloway**[h] **B. Gruey**[h] **P. Freeman**[h] **G. Kramberger**[i] **V. Monaco**[a,b] **M. Obertino**[a,b] **L. Pancheri**[g,d] **G. Paternoster**[c,d] **F. Ravera**[a,b] **R. Sacchi**[a,b] **H.F-W. Sadrozinski**[h] **A. Seiden**[h] **V. Sola**[b] **N. Spencer**[h] **A. Staiano**[b] **M. Wilder**[h] **N. Woods**[h] **A. Zatserklyaniy**[h]

[a] *Università di Torino, Turin, Italy*
[b] *INFN Torino, Turin, Italy*
[c] *Fondazione Bruno Kessler, Trento, Italy*
[d] *TIFPA - INFN, Povo, Trento, Italy*
[e] *Università del Piemonte Orientale, Vercelli, Italy*
[f] *Università di Sabzevar, Iran*
[g] *Università di Trento, Povo, Trento, Italy*
[h] *Santa Cruz Institute for Particle Physics UC Santa Cruz, Santa Cruz, CA, USA*
[i] *Jozef Stefan Institute, Ljubljana, Slovenia*

E-mail: roberto.mulargia@to.infn.it

Abstract: The Ultra Fast Silicon Detectors (UFSD) are a novel concept of silicon detectors based on the Low Gain Avalanche Diode (LGAD) technology, which are able to obtain time resolution of the order of few tens of picoseconds. First prototypes with different geometries (pads/pixels/strips), thickness (300 and 50μm) and gain (between 5 and 20) have been recently designed and manufactured by CNM (Centro Nacional de Microelectrónica, Barcelona) and FBK (Fondazione Bruno Kessler, Trento).
Several measurements on these devices have been performed in laboratory and in beam test and a dependence of the gain on the temperature has been observed. Some of the first measurements will be shown (leakage current, breakdown voltage, gain and time resolution on the 300μm from FBK and gain on the 50μm-thick sensor from CNM) and a comparison with the theoretically predicted trend will be discussed.

Keywords: Particle tracking detectors; detector; fast; silicon; timing

[1]Corresponding author.

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1 Introduction and motivation

Ultra Fast Silicon Detectors (UFSD) aim at measuring with high accuracy both the position and the timing of a particle passing through it. At present, precise timing devices are too large to achieve an accurate position measurement, while accurate tracking detectors determine the time coordinate quite poorly. The inclusion of timing information can drastically improve the reconstruction process of an event in high energy physics experiments (reduction of pile-up effects), mass spectroscopy or positron emission tomography (PET).

The uncertainty of a time measurement is due to: a *Jitter term*, depending on the steepness of the signal and on the noise level; a *Landau term* because of the fluctuation in the ionization process along the track, a *time walk term* caused by variations of the signal's amplitude, and a *TDC term* caused by the binning approximation:

$$\sigma_t^2 = \left(\frac{N}{dV/dt}\right)^2 + \sigma_{timewalk}^2 + \sigma_{Landau}^2 + \sigma_{TDC}^2 \quad . \tag{1.1}$$

While the $\sigma_{TDC} = \frac{\Delta t_{TDCbin}}{\sqrt{12}}$ is unavoidable and the time walk can be corrected by specific electronics, it is crucial to keep the $\frac{N}{dV/dt}$ ratio as low as possible. Therefore the perfect sensor for timing should be characterised by: a linear response (no breakdown), a high signal to noise ratio (moderate gain), a steep signal (small charge collection time).

The thickness, the segmentation and the gain a Low Gain Avalanche Detector (LGAD) can be optimised to make it an excellent candidate for time and position measurements[1]. These devices are similar to avalanche photodiodes (APD), but with a gain layer doping profile designed to obtain a low avalanche multiplication ($\lesssim$ 100) and which can be pixelated in order to improve their spatial accuracy.

2 Gain in a LGAD

The gain layer in a LGAD creates a volume in the bulk of the silicon sensor where the electric field is locally high enough ($E \sim 300kV/cm$) so that the drifting electrons will induce a controlled avalanche without a complete electrical breakdown. It should be noted that the external applied bias voltage must be high enough to saturate the charge drifting velocities ($E_{bias} > 30kV/cm$) and therefore obtain a fast charge collection and a steep signal.
The charge multiplication follows the exponential law

$$N(x) = N_0 \cdot e^{\alpha x} = N_0 \cdot G \tag{2.1}$$

where x is the length travelled by the charge and $G = e^{\alpha x}$ is the gain as function of α, the impact ionisation rate, which depends *exponentially* on the electric field E, as the Chynoweth law states[2]:

$$\alpha_{e,h}(E) = \gamma\, \alpha_{e,h,\infty}\, exp\left(-\frac{\gamma\, \beta_{e,h}}{|E|}\right) \tag{2.2}$$

where $\alpha_{e,h,\infty}$ and $\beta_{e,h}$ are constants of different values for electrons and hole and γ is a constant independent from the charge carrier nature.

2.1 Temperature dependance of gain in a LGAD

The internal gain of a LGAD detector is influenced by the temperature by means of the carriers saturated velocities[3] and the impact ionisation rates, which is related to the reciprocal of the mean free path of the carriers[4]. The study of the temperature dependence on the sensor performance is therefore crucial to calibrate and operate the devices at very low temperatures, as requested by some of the major experiments.

In the simulation software used in the present work, Weightfield2[1] (WF2) [5], four models for the impact ionisation rate as function of the temperature are implemented and currently under study. The *van Overstraeten* and *Massey* models are based on the Chynoweth law (eq.2.2) while the other two, the *Bologna* and the *Okuto* models, each proposed their own law for $\alpha_{e,h}$. All the models, except for the *Massey* model are also implemented in Synopsis Sentaurus[6].
It is important to stress that all the models are empirical, therefore their parameters have been determined by fitting experimental data and are applied as reported in literature, without attempting any tuning. They are applicable for electric fields of the order of $10^5 Vcm^{-1}$ and temperatures around $300K$. The Bologna model was developed to cover a wider range of electric fields 50 – 600 $kVcm^{-1}$ and high temperatures 300 – 700 K.

In the *van Overstraeten model* the temperature dependence lies in the γ factor:

$$\gamma(T) = \frac{\tanh\left(\frac{h\omega}{2kT_0}\right)}{\tanh\left(\frac{h\omega}{2kT}\right)} \quad . \tag{2.3}$$

The *Massey model*[7] removes the γ factor ($\gamma = 1$ in eq.2.2) and expresses a linear dependence on temperature only inside $\beta_{e,h}$.

$$\beta_{e,h}(T) = A_{e,h} + B_{e,h} \cdot T \quad , \tag{2.4}$$

[1]open source avalaible at http://personalpages.to.infn.it/~cartigli/Weightfield2/Main.html

where $A_{e,h}$ and $B_{e,h}$ are constants with different values for electrons and holes.

In the *Okuto model* the impact ionisation rate directly shows the temperature dependence:

$$\alpha_{e,h}(E,T) = a \cdot [1 + c(T - 300K)] \ |E|^{\gamma} \ exp\left[-\left(\frac{b\,[1 + d(T - 300K)]}{|E|}\right)^{\delta}\right] \tag{2.5}$$

where a, b, c, d, γ and δ are constant parameters.

The *Bologna model* is probably the most convoluted one, although α has a simple expression:

$$\alpha_{e,h}(E,T) = \frac{|E|}{a(T) + b(T)\ exp\left[\frac{d(T)}{|E|+c(T)}\right]} \tag{2.6}$$

the parameters $a(T)$, $b(T)$, $c(T)$, $d(T)$ are temperature dependent, with a linear, quadratic or exponential trend[6].

3 Experimental Setup

The sensors are tested in the laboratory for their static characteristics (IV-CV curves) and using a $1064nm$ picosecond laser whose intensity is set to replicate the energy deposition of a minimum ionising particle (MIP). Both the sensor and the amplifier are installed inside a climatic chamber that allows a precise regulation of temperature and humidity and the data acquisition system is automatic (LabVIEW based).

The measured current consists of the sum of the internal current, through the sensor bulk, and the superficial current, through the border of the active area.

The gain is calculated as the ratio between the area of the LGAD signal and the normalised area of a twin diode (without gain layer) signal. In order to get an estimation of the sensor timing capability the time resolution has been measured. The time of a constant fraction of the signal peak is measured and the time resolution is defined as the standard deviation of the distribution of that time.

3.1 The CNM and FBK Productions

The first production of thin $50\mu m$ thick UFSD from CNM (Centro Nacional de Microelectrónica, Barcelona) was presented in 2016[8] ($300\mu m$ thick production in 2014[9]). First beam test results on thin UFSD manufactured by CNM have been obtained in 2016[10].

The $300\mu m$ thick LGAD production from FBK[11] was released in March 2016 and the sensors were engineered and produced by Fondazione Bruno Kessler (FBK, Trento) in the framework of ERC-UFSD/INFN and MEMS/INFN in collaboration with Torino and Trento universities.

A $50\mu m$ thick LGAD production from FBK is expected in early 2017.

4 Measurements of the sensor response versus temperature

The most immediate and predictable effect of temperature on the sensor performance is the decrease of total current for low temperatures. Figure 1 shows the IV curves for a moderate gain (Wafer 3), $300\mu m$ thick, device from FBK at $10°C < T < 25°C$. The IV curve for $T = 10°C$ shows an early breakdown, hint of the increased value of the gain for lower temperatures.

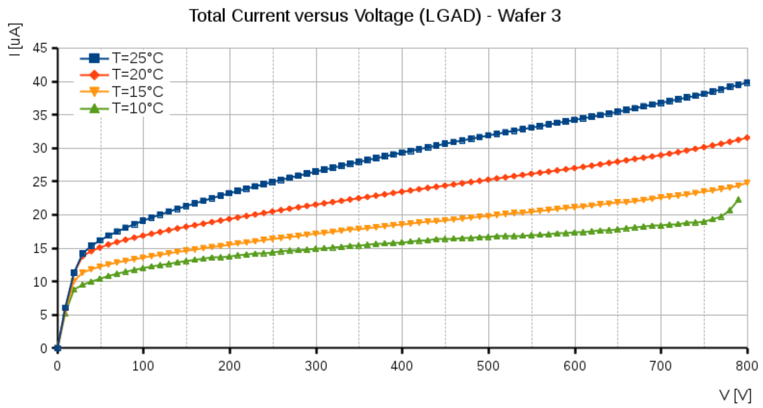

Figure 1. I-V curves at different temperatures in a LGAD with moderate gain (300μm, FBK).

The increase of gain for low temperature is far more relevant in the high gain sensors (right plot in Figure 2) but it is clearly visible on moderate gain sensors (left plot in Figure 2) as well. The right plot in Figure 2 also highlights how the increase in gain generally causes the breakdown to happen at lower bias voltage values.

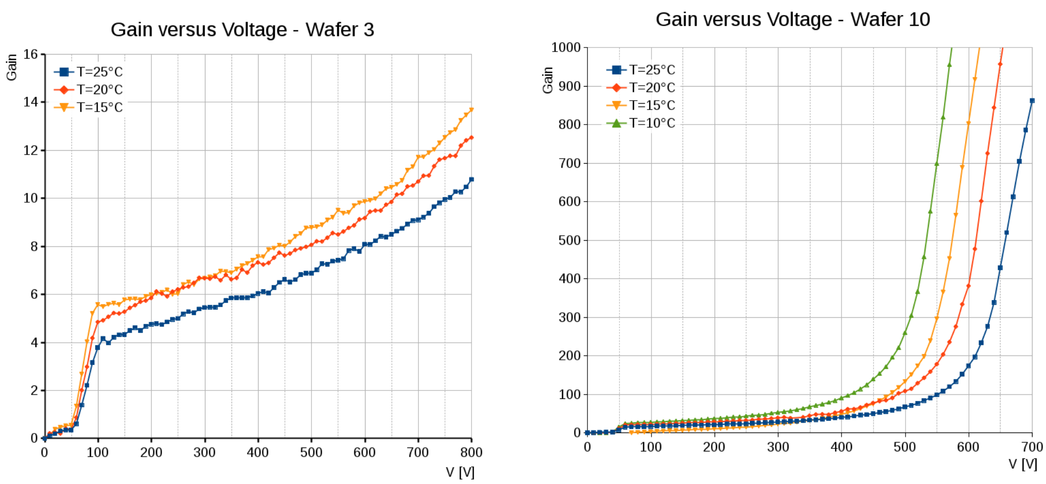

Figure 2. Gain as a function of bias voltage at different temperatures for a moderate gain (left) and high gain (right) device (both 300μm, FBK).

As a consequence of the increase in gain, the time resolution σ_t of the sensor is visibly improved by the changes in temperature (Figure 3).

5 Comparison with simulation

5.1 300μm thick LGAD from FBK

A simulation and a study of temperature dependence of the gain in a LGAD is presented through the implementation of four models in Weightfield2[5] (cfr. Section 2.1). The models immediately

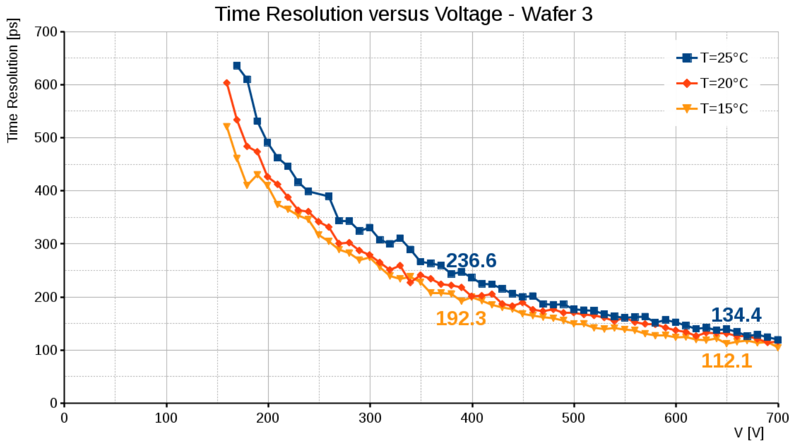

Figure 3. Time resolution for the moderate gain sensor at different temperatures (300μm, FBK).

appear to divide into two families, one consisting of the *Bologna* and *van Overstraeten* models, the other *Massey* and *Okuto* models.

First, the trend of the gain as function of the external bias voltage is shown in Figure 4. As the gain also increases drastically when close to the sensor breakdown it is crucially important that the models will predict the breakdown for the experimentally correct bias voltage value. Both the *Okuto* and the *Massey* models well describe the trend and manage to correctly predict the sensor breakdown. The remaining two models split up for high bias voltage values.

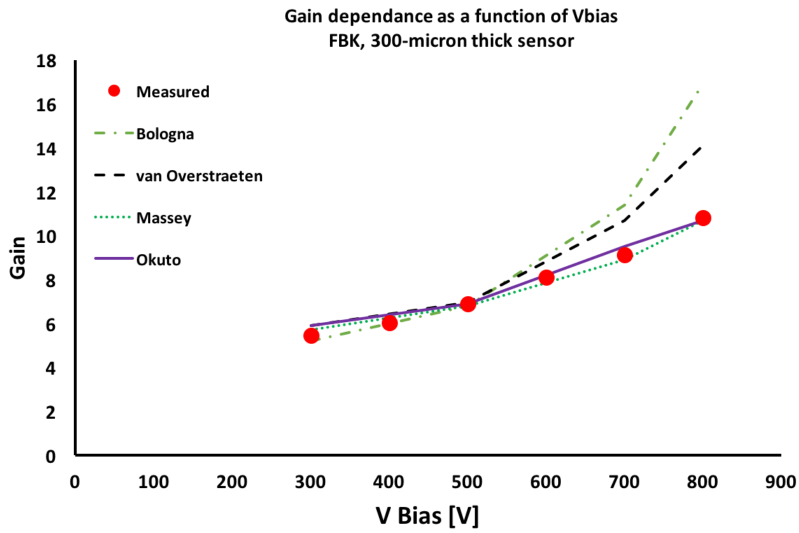

Figure 4. Gain at room temperature as a function of external voltage compared with simulation for 300μm thick LGAD from FBK.

The plot in Figure 5 shows how the two families of models differ in providing a prediction for low temperatures. The *Okuto* and the *Massey* models appear to be in better agreement with the measurement. However, since the experimental points are only four and the error is about 1 unity of gain, further experimental study is necessary to definitely validate or contradict any model.

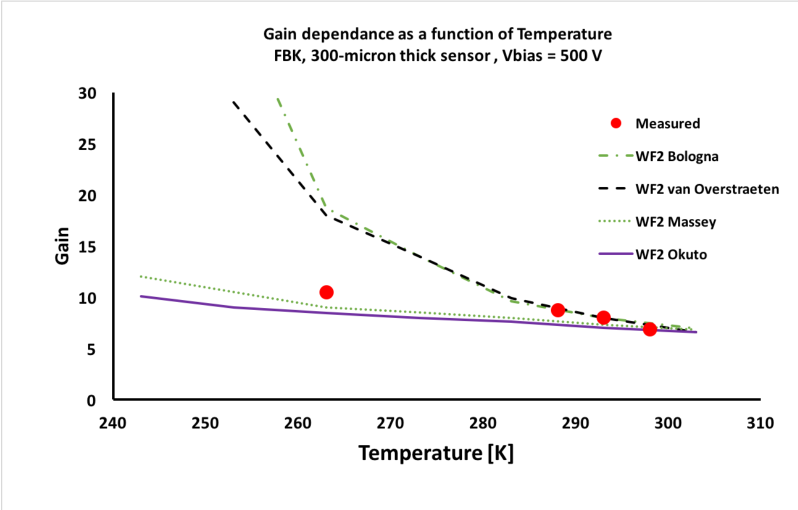

Figure 5. Gain as a function of temperature compared with simulation for 300μm thick LGAD from FBK.

5.2 50μm thick LGAD from CNM

The two plots in Figure 6 show the comparison between the two families of models and the measurements in a much broader range of temperatures for 50μm thick sensors from CNM.
The experimental data appear to be in a far better agreement with the *Massey* and the *Okuto* models.

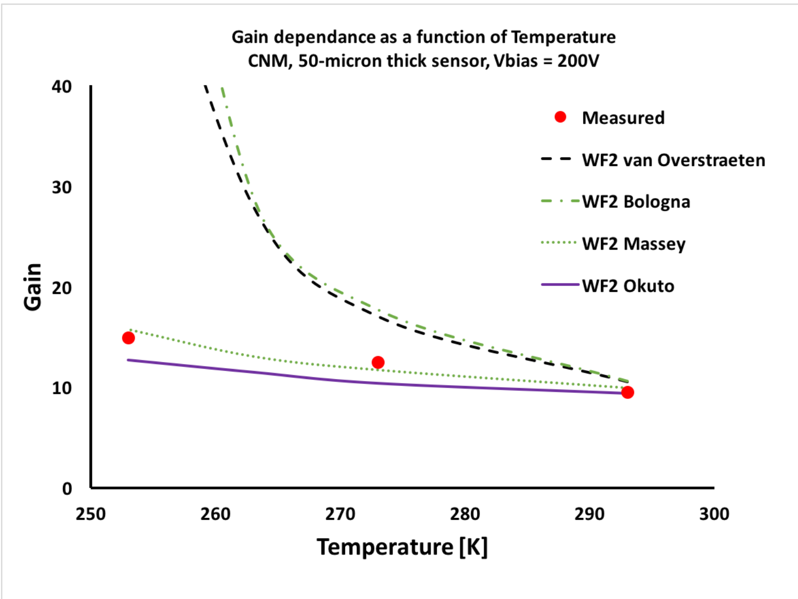

Figure 6. Gain as a function of temperature compared with simulation for 50μm thick LGAD from CNM.

6 Summary

The measurements show a strong dependence of the performance of UFSD on temperature and further studies are necessary in order to understand and better describe the sensor response. Further experimental work might focus on the study on the width of the signal: the increase in the saturation velocity of the carriers due to lower temperatures might induce a shorter and steeper signal. Weightfield2[5] proved itself to be a valuable assist in this study and offered a good description of the performance of the thin sensors; further work in improving it would hence benefit the knowledge of these performances.

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