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Fast Timing with Induced Current Detectors

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Abstract

Vertically integrated (3D) combinations of sensors and electronics provide the ability to fabricate small, fine pitch pixels with very small total capacitance monolithically integrated with complex circuitry. The small capacitance, enabled by the fine pixel pitch and low interconnect capacitance available in 3D hybrid bonding, provides excellent signal/noise with moderate power. This combination enables fabrication of integrated sensors and electronics with both excellent position and time resolution. We describe the capabilities of such a system and the limitations imposed by geometry and power. We describe how a similar geometry can be used to provide very fast timing of x-ray arrival in a thick sensor by utilizing the transient induced current in a field of pixels.

Keywords: 3D Integration, Pixel Detector, Induced Currents, X-ray Imaging

1. Signal, noise and small pixels

There is increasing need for precise time and position resolution in dense, complex experimental environments in particle physics, nuclear physics, and x-ray science. The recent focus in particle physics has been on the use of amplification to improve signal/noise and the deployment of thin detectors to minimize charge collection time [1, 2, 3, 4]. We argue that emerging three dimensional

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integrated circuit technology (3DIC), which can provide dense, low capacitance interconnects and complex in-pixel processing, can potentially solve many of these problems. In particular fast electronics integrated into small low capacitance pixels can enable precise timing and extraction of complex information in both thick and thin silicon detectors.

In a system where the timing resolution is dominated by noise-associated jitter we can express the time resolution in terms of detector and amplifier parameters as:

$$\sigma_t \approx \sigma_n \frac{\delta V}{\delta t} \approx t_r \frac{noise}{signal}, \sigma_n^2 \approx \frac{C_L^2(4kTA)}{g_m T_a}, \sigma_t \approx \frac{C_L}{\sqrt{g_m t_a}} \frac{\sqrt{t_a^2 + t_d^2}}{signal} \qquad (1)$$

[5, 6] Where σ_t is the time resolution, σ_n is the system noise, $\frac{\delta V}{\delta t}$ is related to the amplifier and detector rise times, t_a and t_d, C_L is the load capacitance, g_m is the front end transistor transductance and $4kTA$ is associated with the thermal noise of the amplifier. To achieve good time resolution we want to maximize signal to noise, minimize risetimes, maximize g_m (which is related to front-end transistor current), and minimize capacitance. Low Gain Avalanche Diodes (LGADs), currently being studied for the LHC upgrades, use avalanche gain to increase the signal by factors of 10-20. Time resolution of these devices is generally limited by ionization sampling statistics (sometimes called "Landau noise") rather than electronics timing jitter. The current generation of LGADs typically have large $\approx$ 1mm pixels, with the pitch limited by the need to have adequate fill factor given the space taken by edge field termination of the pixels. This leads to capacitances greater than a few pf, increasing the overall noise [1, 2, 3, 4]. For LHC applications the signal gain dominates, and there is an overall improvement in time resolution in spite of the large pixel capacitance. However there are tradeoffs in fill factor, power consumption, and position resolution. LGADs suffer reduced gain at high levels of irradiation due to acceptor removal in the gain layer. New developments, such as AC LGADs [7] and Inverse Low Gain Avalanche detectors (iLGAD) [8] can avoid the restrictions due to edge terminations and will enable finer pitch.

If we instead employ small pixels, the lower load capacitance, which scales roughly as the dimension squared, will dramatically reduce the front-end noise. Since noise also scales as $\frac{1}{\sqrt{g_m}} \approx \frac{1}{\sqrt{current}}$ one can reduce the power per pixel in partial compensation for the increased number of pixels and retain a gain in time resolution to the point where factors other than jitter, such as fluctuations in ionization density, will dominate.

2. Methodology

We explore a simple system using 2 and 3 dimensional TCAD models of a 3×3 (3D) or 1×9 (2D) array of pixels with 25 micron pitch. A $4fc$ pulse is injected, either uniformly through the depth (a "MIP") or localized at a specific depth (an "x-ray"). We extract the capacitance and resulting pulse shapes from the TCAD model. The resulting pulse is injected into a SPICE model of a charge sensitive amplifier in 65 nm technology including noise. The current supplied to the input transistor is about four microamps. We then examine the resulting time jitter. Note that in this simulation the pulses are monoenergetic, there is no time walk or ionization fluctuation component of the resolution. Figure 1 shows the resulting (jitter-only) time resolution for a 50 micron thick detector, with 25 micron pixels biased at 200 Volts. The resulting time resolution is 16 ps, indicating that noise-induced jitter will likely not be a dominating factor for MIP timing with small pixels.

3. 3D Integration

Fermilab has been involved the development of 3D sensor/ASIC integration for almost a decade and demonstrated the first 3-tier (sensor, two tiers of 130 nm CMOS) electronics-sensor stack including a design with 24 micron pixels including ADC and TDC [9, 10]. Importantly, the noise in the hybrid (DBI®) bonded VIPIC 3D assembly is almost a factor of two lower than the equivalent conventionally bump bonded parts due to lower pixel load capacitance. The lower capacitance was due to the small (few micron) hybrid bonded interconnects which add only a few femtofarads load compared to the > 100 ff

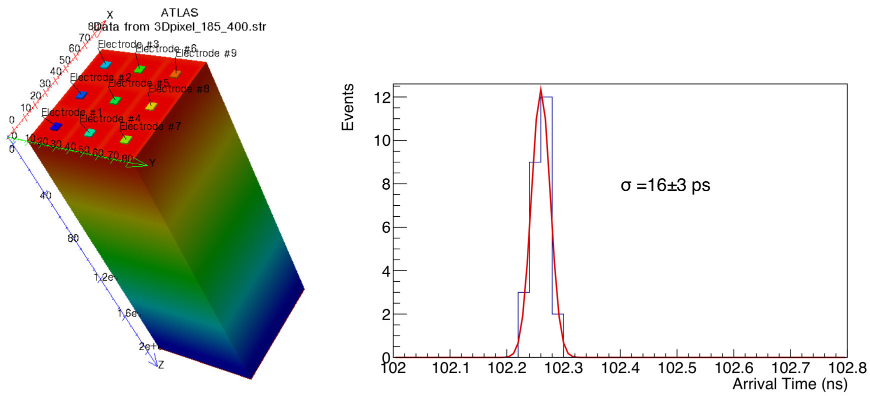

Figure 1: Left - TCAD model of the detector. Right - Electronics time resolution after the preamp.

capacitance of the solder bumps and associated pads. Similar small values of load capacitance can be achieved in CMOS MAPS sensors if the collection node is kept small. In CMOS MAPS this requires careful engineering of the depleted region of the epitaxial layer to insure that there are large enough drift fields to insure fast charge collection.

4. Induced currents and X-Ray timing

Here we consider the application of these concepts for x-ray timing detectors. These detectors must be thicker than those used for MIP tracking to achieve reasonable efficiency for high energy x-rays. In this case we consider a 200 micron thick substrate. The current induced on an electrode in a multi-electrode system depends on the coupling between the moving charge and the electrode (Shockley-Ramo theorem) [11, 12]. This current depends both on the velocity of the charge and the value of the effective "weighting" field. If the pixel pitch is small compared to the thickness, charge moving far from the surface will induce roughly equal currents in several electrodes surrounding the nodes collecting the charge. This current has a very fast rise, but will integrate to zero in all but the charge collecting electrodes. An example is shown in figure 2. The initial fast current spike is similar for all electrodes where the pitch is small compared to the depth of the hit. If the detector has low capacitance coupled to fast electronics this induced current signal can be used to provide a time stamp for the hit signal.

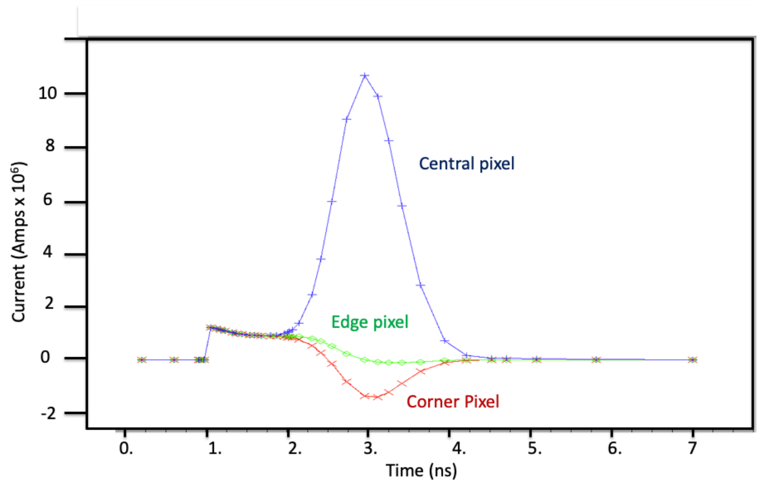

Figure 2: Signal for an x ray deposited at 190 microns in a 200 micron thick detector with 25 micron pitch pixels biased at 400 Volts.

If we consider the case of timing for high energy x-rays, the long x-ray absorption length conflicts with the requirement for thin detectors assumed to be needed for fast timing. This is not necessarily the case if we are able to utilize the induced currents in neighbor pads. The bipolar signals in neighbor pixels can be used to extract multiple time stamps for a single x-ray. Those time stamps can be latched only if the delayed signal from the central pixel exceeds threshold. The time between the initial induced current signal and the peak induced current in the charge collecting electrode indicates depth of the x-ray hit. Figure 3 shows an example of a simulated x-ray hit in a 200 micron thick detector the associated induced signal in the central and neighbor pads, and the resulting time resolutions. Note that the edge electrode is one of a possible 8 neighbor and 14 next-neighbor electrodes with useful induced current. The number of useful time measurements depends on depth of charge deposit, pixel size, and signal/noise.

Implementation depends on the details of the beam rate, detector occupancy, and x-ray energy. Drift fields can be shaped by detector bias and type. For example an n-on-n detector will have the maximum field near the backside, emphasizing the induced signals, whereas a n on p detector will have it's maximum field near the top surface. Pixel pitch will determine the multiplicity of hit pixels as a function of depth.

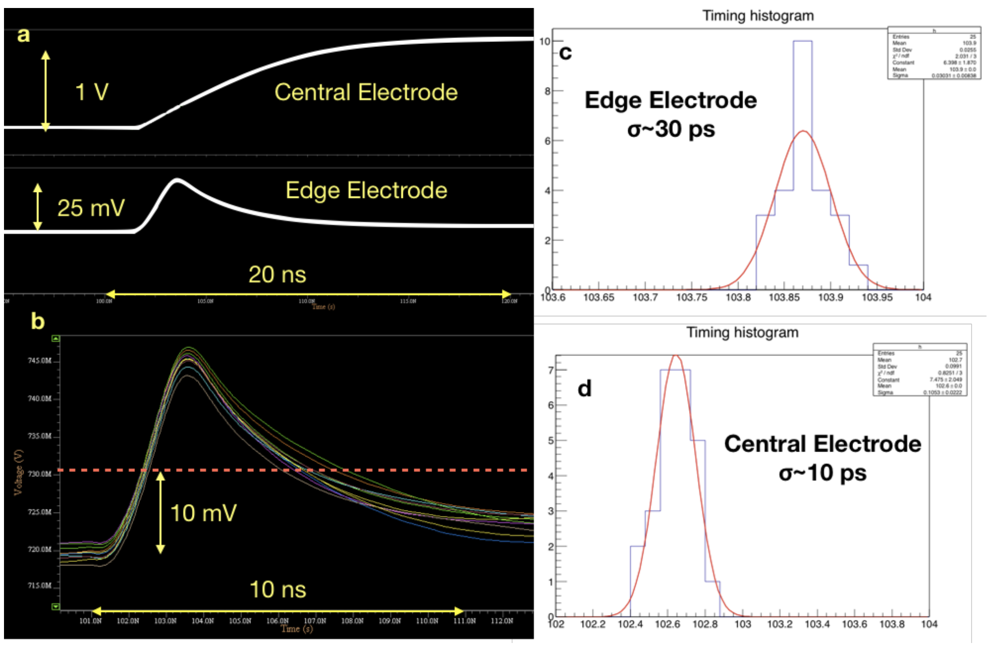

Figure 3: Pulse shapes and timing for a central (charge collecting) and edge (induced current) electrode for a x-ray like MIP energy deposit at 185 micron depth in a 200 micron thick detector. a) Pulse shapes for the central (top) and edge electrode. b) Pulse shape for the edge electrode for 25 pulses including noise. The threshold is set at 10 mV above baseline c) The resulting time jitter for the edge electrode in plot b d) The time jitter for the central electrode with a threshold of 130 mV above the baseline.

If only high rate is needed, e.g. for single photon counting, a fast peak can be achieved by minimizing the deep induced signals, shaping the field to peak near the surface. Field peaking can be enhanced by using a thin ($< 2\mu m$) moderately doped ($10^{14} - 10^{16}/cm^3$) layer buried several microns under the top electrode. This can be achieved by varying the dopant density in the gas during top layer epitaxy. In this arrangement, Gauss's law tells us that the difference between the upper field and the lower field is proportional to the number of ionized atoms in the (fully depleted) epitaxial layer. This allows us to engineer the relative value of fields in various regions of the detector. The field region defined by the epitaxial layer can be designed for avalanche gain. An avalanche device based on a buried epitaxial layer is being investigated as an alternative, more flexible, variant of the standard reach-through LGAD [1] [13]. Such an arrangement could function as a silicon TPC, with the bulk of the signal induced in the short time when charges are drifting in the high field region near the electrodes.

5. Example - Complex events in HEP

Collider based experiments have to deal with increasingly complex events with HL-LHC experiments integrating 200 interactions per 25 ns beam crossing [14]. The CMS experiment is addressing this by using stacked, spaced sensor arrays to distinguish low from moderate ($\geq 2GeV$) momentum tracks [15], reducing the bandwidth sent off-detector to the level 1 trigger. This takes advantage of the fact that the bend angle is correlated with the track momentum. A future alternative is to use a single, thicker detector with small pixels to distinguish pulse shapes of tracks as a function of the angle of incidence. An example of these shapes is shown in Figure 4. Information on sets of pixel hits, for example the time between the initial current pulse and the peak current, can be correlated in the readout chip to measure the track angle. Such a "smart" detector may be crucial in extremely challenging applications such as a future muon collider where the background tracks from muon beam decay-induced showers that enter the detector in a range of angles must be rejected by a factor of $100 - 1000$.

[1] In an reach-through avalanche diode the gain region is defined by a deep implant through the top surface

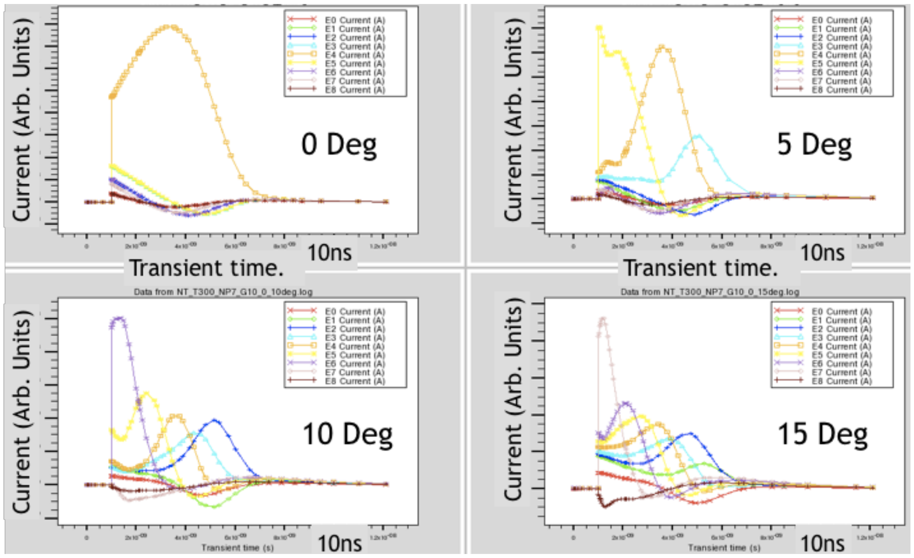

Figure 4: Currents induced by a uniformly ionizing track at at various angles with respect to the surface or a 300 micron thick, 25 micron pitch sensor. The track at 0 degrees is incident on electrode 4 (large gold trace in the 0 degree plots).

6. Conclusions

Small pixel detector systems provide a way to address some of the extreme challenges of future experiments including fast timing, complex event topologies, and radiation hardness. For x-ray imaging they can enable fast timing and high rates with thicker, more efficient detectors. Much of the technology is already in place. Sensor thinning and bonding, 3D integration, and fast timing circuitry have all been demonstrated and are under continuing development [16]. The use of induced currents requires signal processing in the sub-nanosecond regime. A 3D stack with separate analog and digital tiers is the most natural implementation. The most significant challenge may be management of power consumption and tradeoffs between speed and power.

This work provides some “toy” models of these systems, but much more real engineering work is needed. There are many system issues - power, cooling mass, dead areas, support geometries, amplifier and circuit designs - that need to be studied. They can only be understood within a specific context. A “real” application, perhaps a future muon or high luminosity hadron collider or high rate x-ray imaging detector, would be a valuable focus for future work.

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