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Novel Sensors for Particle Tracking: A Contribution to the Snowmass Community Planning Exercise of 2021

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ABSTRACT

Four contemporary technologies are discussed in the context of their potential roles in particle tracking for future high energy physics applications. These include sensors of the 3D configuration, in both diamond and silicon, submicron-dimension pixels, and thin film detectors. Drivers of the technologies include radiation hardness, excellent position and vertex resolution, simplified integration, and optimized power, cost, and material.

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1 Introduction

Research in particle tracking detectors for high energy physics application is underway with a goal of improving radiation hardness, achieving improved position and vertex resolution, simplifying integration, and optimizing power, cost, and material. The four technologies described here approach these goals in complementary ways.

2 Silicon Sensors in 3D Technology

Boscardin, Dalla Betta, Hoeferkamp, Seidel, Sultan

Silicon sensors of the 3D technology [1] are employed in LHC experiments [2, 3] to provide radiation tolerant particle tracking at integrated fluences in the regime of $10^{16} n_{\mathrm{eq}}/\mathrm{cm}^2$. The decoupling of the depletion depth from the sensor thickness allows operation at bias voltages below breakdown despite very high integrated fluence, with significant savings on power dissipation, and the small inter-electrode distance suppresses the effect of radiation-induced charge trapping. The ATLAS IBL sensors, for example, are implemented in p-type with 230μm thickness and column electrodes of diameter approximately 10μm, separated by approximately 62 microns. A slim edge of 200 microns is employed. Designs for application to the HL-LHC, where innermost tracking will be exposed over the course of 10 years to fluence $2.3 \times 10^{16} n_{\mathrm{eq}}/\mathrm{cm}^2$ [4], are more aggressive still, in anticipation of conditions in which the carrier lifetime will be reduced to 0.3 ns, corresponding to a mean free path of 30 microns. Up to 200 interactions per 25 ns bunch crossing are expected at the HL-LHC. Small-pitch 3D pixels ($25 \times 100\ \mu\mathrm{m}^2$ or $50 \times 50\ \mu\mathrm{m}^2$) have been developed to this purpose, with inter-electrode distances of approximately 30 microns [5] and a slim edge of 150 microns, and are currently in the pre-production phase for the ATLAS ITk.

Plans [6] for future facilities such as the FCC-hh anticipate a lifetime integrated luminosity of 30 ab^{-1}, predicting integrated fluence at the innermost tracking volume approaching $10^{18} n_{\mathrm{eq}}/\mathrm{cm}^2$. Estimates [7] of the pileup conditions are on the order of 1000 events per crossing. Continued development of silicon sensors of the 3D technology presents prospects both for restoration of signal loss in high radiation environments, and for separation of pileup signals by precision timing. Measurements [8] carried out on $50 \times 50\ \mu\mathrm{m}^2$ cell 3D sensors have shown signals with a full width of 5 ns, and a rise time of 1.5 ns, with a timing resolution of 30 - 180 ps (depending on the signal amplitude); this is a mode of operation comparable to that achieved by low gain avalanche detectors — but lacking gain — with the advantage of higher radiation tolerance and better fill factor. The standard column configuration of 3D has the disadvantages, however, that the electric and weighting fields are non-uniform, leading to position dependence of the pulse rise time; this is the limiting factor on the timing resolution. New geometries [9, 10] involving p-type trench electrodes spanning the entire length of the detector, separated by lines of segmented n-type electrodes for readout, promise improved uniformity and better timing resolution combined with further increased radiation tolerance. Nevertheless, at this time, trenched electrodes cause higher capacitance and introduce larger dead volumes within the substrate. Device optimizations, especially in terms of geometrical efficiency, remain to be carried out. In addition, this problem can be tackled at the system level by tilting the sensor plane with respect to the particle direction, so that a larger fraction of the charge is generated within the depleted volume, and using multiple planes of sensors with an offset between the electrodes, so all tracks would traverse several planes without crossing the electrodes [11].

3D columnar pixels with internal gain [12]-[14] offer an alternative approach to signal restoration at high fluence. When implemented with very small inter-electrode separation, approximately 15 microns or less, these devices can achieve controlled charge multiplication at voltages on the order of 100 V, both before and after irradiation. Moderate gain values can be achieved, sufficient to compensate the loss of charge signal due to irradiation of these thin (approximately 100 μm) devices. Design optimization continues with a goal of achieving uniform gain throughout the cell active volume, also benefiting from the wider operating range that is possible due to increasing the breakdown voltage.

The goal of this research is to advance one or two 3D technologies in silicon for tracking particles, able to operate with adequate signal-to-noise ratio at fluences approaching 10^{18} $\mathrm{n_{eq}/cm^2}$, and timing resolution on the order of 10 ps. Planned research activities include TCAD simulations, process optimization and fabrication of several generations of prototypes, and thorough characterization of the prototypes before and after irradiation to extreme fluences.

3 3D Diamond Detectors

Kagan, Trischuk

By 2028, experiments operating at the HL-LHC must be prepared for an instantaneous luminosity of $7.5 \times 10^{34}/\mathrm{cm^2/s}$ and charge particle fluxes of GHz/cm^2. After these doses, all detector materials will be trap-limited, with the average drift distance a free charge carrier travels before it gets trapped being below 50 μm [15]. 3D sensors reduce the drift distance the charge carriers must travel to reach an electrode to much less than the sensor thickness. This is particularly beneficial in detectors with a limited distance free charge carriers travel, such as trap-dominated sensor materials like heavily irradiated silicon and pCVD diamond, where the observed signal size is related to the mean free path divided by the drift distance. Under these circumstances one gains radiation tolerance (larger signals) by keeping the drift distance less than the mean free path. With the 3D geometrical structure, charge carriers drift inside the bulk parallel to the surface over a typical drift distance of $25 - 100$ μm instead of perpendicular to the surface over a distance of $250 - 500$ μm.

The RD42 collaboration has studied novel 3D detector designs in diamond, to extend the radiation tolerance of diamond to fluences greater than 10^{17} hadrons/cm^2, exceeding the HL-LHC doses. The detector design places column-like electrodes inside the detector material using a 130 fs laser with a wavelength of 800 nm. After focusing to a 2 μm spot, the laser has the energy density to convert diamond into an electrically resistive mixture of different carbon phases [16]. A Spatial Light Modulator (SLM) [17] is used to correct spherical aberrations during fabrication. This helps to achieve in 50 μm $\times$ 50 μm cells a high column yield of $\geq$ 99.8%, a small column diameter of 2.6 μm, and a resistivity of the columns of the order of $0.1 - 1$ Ωcm. In this detector geometry, the drift distance an electron-hole pair must travel to reach an electrode can be reduced below the mean free path of an irradiated sensor without reducing the number of electron-hole pairs created. In a detector with 25 μm $\times$ 25 μm cells, the maximum drift distance for charge carriers that go into the saddle point region is 25 μm, and 17.5 μm for charge carriers that avoid the saddle point. The goal of this research project is to create a detector that is essentially immune to radiation doses at the level of 10^{17} hadrons/cm^2. Initial tests have shown that after 3.5×10^{15} n/cm^2, the 3D geometry with 50 μm × 50 μm cells has better than three times less charge loss than a planar diamond detector after normalizing both unirradiated devices to a relative charge of 1. Furthermore the charge in the unirradiated 3D device is twice as large as that in the planar device. Thus, in addition to having twice the charge, the 3D device also has better than three times less damage, due to the shorter drift distance. In order to achieve the 10^{17} hadrons/cm^2 goal, completion of the design of 3D diamond devices with 25 μm × 25 μm cells and testing of these devices after irradiation with 10^{17} hadrons/cm^2 is proposed.

4 Beyond CMOS: Submicron Pixels for Vertexing

Fourches, Renard, Barbier

Development of a submicron position sensitive vertex detector for the future linear collider experiments is proposed. Although improved relative to their predecessors, the present vertexing pixel detectors at the Large Hadron Collider suffer from low position resolution. The objective of vertex detectors is to enable the accurate secondary vertex determination that is crucial for b-tagging [18, 19] in the case of high transverse momentum (p_T) events. The heavy quark events are characterized by a relatively high lifetime that leads to a secondary vertex distinct from the interaction point [20]. For accurate track reconstruction, it is necessary to improve point to point resolution well below the 5 micrometer limit. In the framework of ILD, development of a pixel detector based on the DoTPiX structure is proposed.

Accurate track reconstruction with a vertex detector is possible using a small pitch detector, which in the case of the ILC can reduce the multiplicity (in which a pixel is hit several times). This is crucial for the ILD where the readout of the detector is made only after several bunches. With a track fit, displaced secondary vertices can be evaluated, using an impact parameter technique to select the right track, and the analysis of the full decay of the particle can be done, using all necessary jets. In addition, isolated tracks can be tagged in order to reduce fake events. The vertex detectors implemented in the LHC experiment are based on a hybrid design. The high particle rate at the LHC induces a large dose in the detector where non-ionizing energy loss damages the detector material and the electronic readout. Special techniques have been used to circumvent these effects with the use of hardened processes [21] and adequately doped silicon pixel structures [22]. To accommodate the LHC beam crossing time, detectors use a triggered readout involving a fast readout chip (ROC). The on-pixel electronics has to be elaborate to collect the information of all the pixel hits' output when triggered. For the technologies available from the late 1990's to the early 2000's, this requirement excluded small pitch pixel detectors. Even with pitch of tens of microns, the number of channels (pixels) is of the order of tens of millions in the inner vertex detectors.

The constraints are different for the ILC where more precise reconstruction is the objective. The advantage of vertex detectors with much improved resolution will be good secondary vertex reconstruction with an accuracy of 0.5 micrometers (or in time at the speed of light, of 1.6 fs). This cannot be matched by a timing procedure, which can only estimate the position of the interaction point in the beam-crossing zone. This zone will be reduced at the ILC compared with the LHC. Additionally, short-lived particles can be tagged at this stage. Significant features of this proposal include the following.

The detectors close to the primary interaction point can detect low-mass charged particles that can escape the tracker due to the effect of the magnetic field on low-mass particles [23]. Tagging such particles can be established with a good vertex detector [24]. These particles can produce disappearing tracks. The energy of these long-lived particles cannot be determined easily as they escape calorimetry. The only possibility, besides using time-of-flight, is to add extra layers to the vertex detector to match the trajectory.

The operation of a vertex detector in a trigger-free mode means that many bunch crossings will be combined (pile up) before being output and reset. This makes the use of very small pixels necessary to avoid multiple hits in a single pixel. The pitch has to be reduced to match these requirements, and only a fully monolithic pixel can be used for this purpose.

The reconstruction of tracks with relatively low p_{T} near the interaction point will be easier with a pixel detector with large enough aspect (height/width) ratio. A small pitch (less than 1 micrometer) with a height up to of 10 micrometers (the sensitive zone) opens up such a possibility.

A pixel design has been proposed [25, 26]. The necessary simulations have been made to assess the functionality of the proposed device. The next step is to find out what is the best process to obtain the functionality and to reach some required specifications.

5 Thin Film Detectors

Kim, Metcalfe, Sumant

Nanoscience technologies are developing new cutting edge materials and devices for a wide range of applications. HEP can take advantage of the many advances by looking toward thin film fabrication techniques to implement a new type of particle detector. Thin Film (TF) Detectors have the potential to be fully integrated, large area, low power, with low dead material, and low cost. The present goal is to investigate potential research paths using thin film technologies and to identify and characterize the performance benefits for future particle experiments.

A new detector technology is proposed based on thin films that is aimed at dramatically improving the precision of particle detectors by greatly reducing the mass of the detector [27]. Cleaner signatures of the particles from the primary collision will be obtained by reducing those particles' interactions with dead material, which will improve reconstruction efficiencies and resolutions. Thin Film technologies could potentially replace the entire detector including all the services. If a thin film detector could be printed in large areas (square meters), it is estimated that the cost would be reduced to less than 1% of the current cost. If the nuclear interaction length can be decreased by a factor of 10, then the track reconstruction efficiencies would reach 99% and enable a host of new measurements and searches.

Thin Film technology presents one possible solution to achieve these performance milestones. TF transistors (TFTs) were first conceived in the 1960s by Paul Weimer [28]. By the 21st century, fabrication technologies had improved enough to make it competitive with existing technologies. TFTs are the basis of technologies such as Liquid Crystal Display (LCD) screens, solar cells, and light emitting diodes. It is a rapidly growing technology area with a large market base and has corresponding investment in large scale fabrication and industrialization. Ultimately, the broader interest of these technologies enables HEP to leverage the investments in commercialization as well as the R & D into materials, tools, and techniques.

Some of the advantages of TFs are optical transparency, mechanical flexibility, high spatial resolution, large area coverage, and low cost relative to traditional silicon-based semiconductor technology. TF technology uses crystalline growth techniques to layer materials. Monolithic sensors can be fabricated using layers of thin film materials for particle detection with layers for amplification electronics. The advantages of a detector made with this type of technology include single piece large area devices (on the order of a few square meters), high resolution ($< 10\ \mu$m), low cost (100 times less than that of Si-CMOS), low mass, and high curvature for a cylindrical, edgeless design [29]-[31].

Fabrication processes such as chemical bath deposition and close-space sublimation on a substrate material can produce thin films with a high degree of precision. Here, the crystalline structure is grown in layers, avoiding drilling and etching techniques standard in traditional silicon fabrication; consequently, TF processing is much less expensive.

Thin film electronics can be vertically integrated with a thin film sensor if the fabrication techniques are compatible. This would allow vertical integration of sensor and pixel electronics. Further vertical integration using through-vias would enable signals to pass from one layer to the next, thus enabling several levels of electronic processing. Typical front-end ASIC functions could be integrated into the monolithic structure as well as higher-end processing to perform functions such as data aggregation and region-of-interest processing. Such processing would reduce the number of transmission lines integrated into a top layer and further reduce the material inside the detector volume.

The transistor is the most basic unit that determines the power consumption in electronics. Complementary Metal Oxide Semiconductor (CMOS) is a low power technology and is the current mainstay for most of commercial electronics. There are, however, many types of transistor technologies that can outperform CMOS. Silicon Germanium (SiGe) Heterojunction Bipolar Transistors (HBTs) are another class of transistor that typically boast faster speeds and lower power consumption [32]-[34]. Fin-Field Effect Transistors (FinFETs) are being pursued as the next ultra-low power technology and are manufactured by companies such as IBM and Motorola. However, the most transformational transistor is the Thin Film Transistor (TFT), which is breaking records in terms of size and power. All of these technologies have the potential for reducing the power (and the copper in the transmission lines) over the current technologies.

Thin Film Detectors have the potential to replace a wide range of detector types from tracking to calorimetry. The present goals are to identify key areas of research within Thin Film technologies, quantify the key requirements from different types of experiments, and evaluate the potential physics impact.

6 Conclusion

Four contemporary technologies are under development for applications at future high energy physics experiments. Collaborators interested in joining any of these efforts are welcome.

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