Vertically Aligned Carbon Nanotubes as Pixel Detector Substrate

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Introduction

In Transmission Electron Microscopy the modulation transfer function (MTF) and the detective quantum efficiency (DQE) are two of the key performance indicators for a detector system.

Both, the electrons directly backscattered from the active sensor and those backscattered from the material below the active sensor, contribute to the reduction of the performances by reducing the MTF and in turn the DQE.

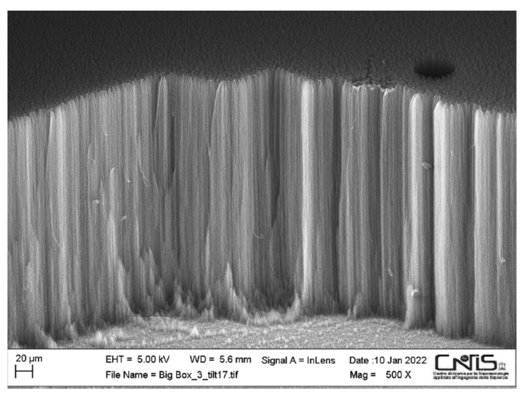
Active electronics on the pixel sensor itself also require cooling. The reduction of the backscattering and the thermal control of semiconductor detectors in vacuum are two common problems to face when designing high resolution, low-background and low-noise particle detectors.

It's well known that low-Z materials, such as Aluminum or Beryllium reduce the intensity of the backscattered radiation (electrons or photons) as the radiation travel deep into the media and the fraction of the backscattered radiation is reduced, but not totally suppressed.

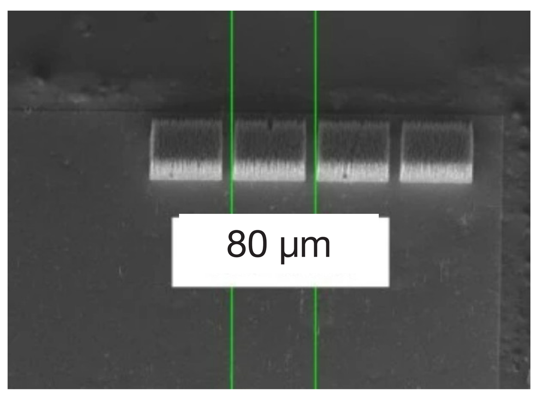
Vertically Aligned Carbon Nanotubes

Carbon Nanotubes (CNTs) posses extraordinary electrical conductivity, heat conductivity, mechanical and chemical properties. Vertically Aligned Carbon Nanotubes (VACNTs) in particular are one dimensional structures, where the different nanotubes are grown next to each other by chemical vapor deposition (CVD).

VACNT layers have shown outstanding directionality properties in ion channeling **[dacunto],** electron penetration **[kyriakou]** and other applications **[nojeh]**. The layers can be grown up to a thickness of 1 mm and can be segmented in "bumps" **[yap]**.

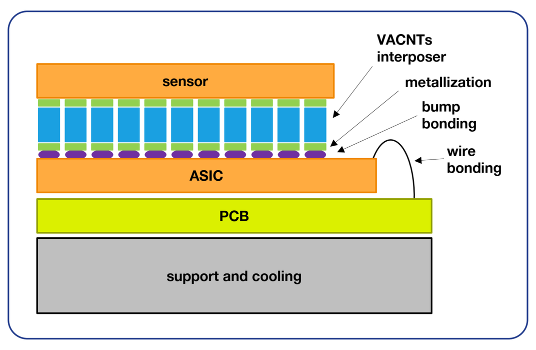


VACNT forest [pandolfi]

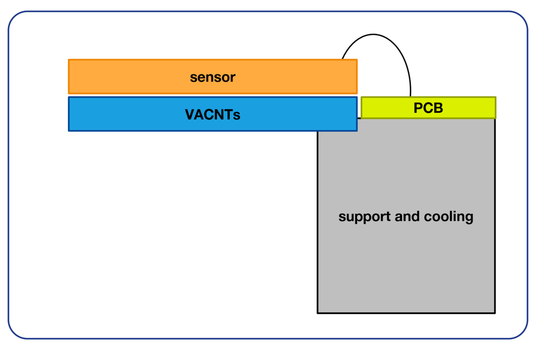


Segmented VACNTs bumps [yap]

VACNTs could be used as the detector substrate or, in the case of hybrid detectors, as a pixelated interposer between the ASIC and the sensor as illustrated below.



VACNTs in Hybrid Pixel Detectors



VACNTs in MAPS Detectors

In both cases the VACNT layer would assure an optimal heat extraction channel when coupled with an active cooling system.

A decrease in the intensity of the direct backscattering radiation (photon and/or electrons) entering the detector from the back would be also granted by the low atomic number of carbon.

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Simulations

Model

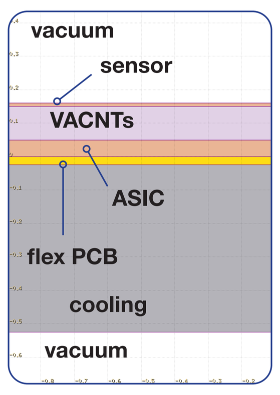
The angular distribution and the energy spectrum of the backscattered radiation are not uniform. Both have an impact on the correct determination of the impact point of the original electron.

In order to start exploring the possibility of using this structure as an interposer between the ASIC and the sensor or as a detector substrate, we need to understand the charactерstics of the radiation backscattered to the sensor.

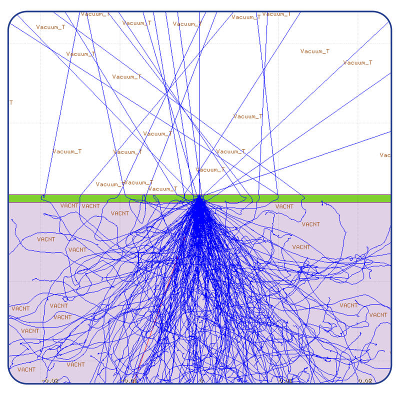
I simulated the interaction of a 300 keV pencil electron beam impinging on a simplified detector assembly composed by:

- an active sensor (different thicknesses and materials);
- a 1 mm thick VACNT substrate (modelled as graphite with scaled density);
- a 500 µm thick silicon ASIC;
- a 250 µm thick flex PCB;
- a 5 mm thick Aluminum support.

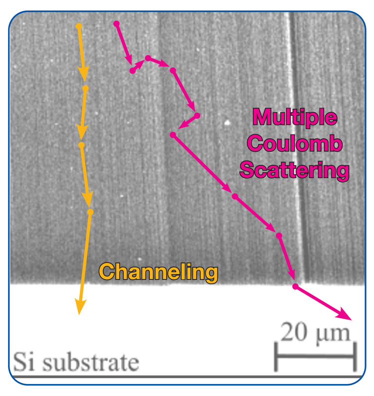
For this first investigation step no further details (such as metallization layers, bump bonding, etc…) were included.



Simulation Model



Examples of electron tracks



Simulation Model

The selected sensor configurations used for this study were:

- Si (thicknesses: 35, 50, 100, 150, 200 and 300 µm);
- GaAs (thicknesses: 10 µm and 250 µm);
- CdTe (thickness: 750 µm).

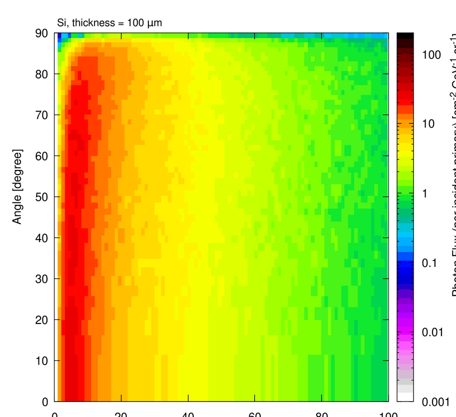
Thicker high-Z sensor configurations were included as a reference to evaluate the effects of the sensor on the backscattering on the primary radiation.

The 10 µm thin GaAs sensor configuration might appear quite exotic and unrealistic. It is included to investigate what could happen if the growth of a thin GaAs sensor **[ranngel]** could be coupled with the growth of VACNTs on GaAs **[engel]**.

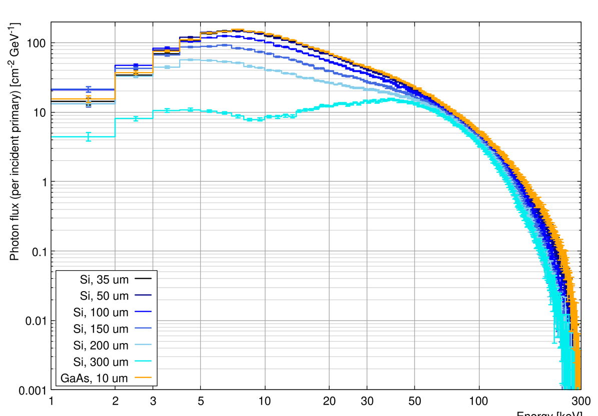
The VACNT were simulated as an amorphous material with an adjusted material density. The simulations were performed using the Fluka Monte-Carlo framework **[fluka]**.

Backscattered Photons

Electron detectors are also sensitive (fully or in part) to the photon part of the backscattered radiation. Its impact is at least two order of magnitudes lower than the backscattered electron, both because of the fluence and the limited sensitivity that a thinned detector has for the energies at play.



Distribution of the backscattered photons as a function of energy and exit angle



Distribution of the backscattered photons as a function of energy

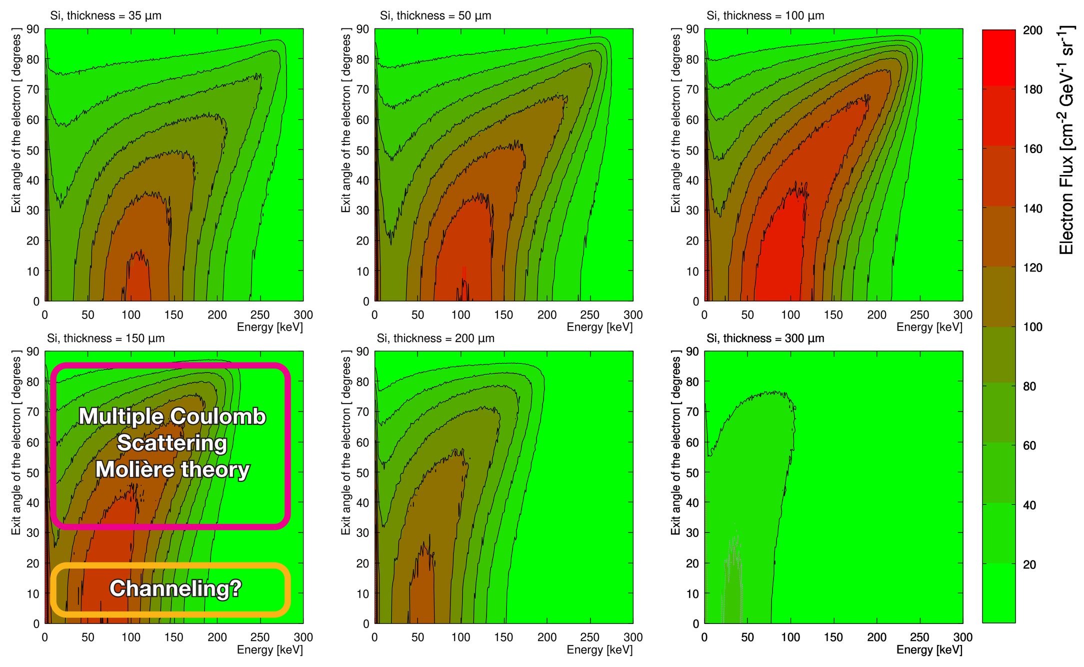
The angular distribution of the backscatter photons is typically isotropic.

Above 50 keV, the photon flux exiting from the VACNT surface decreases almost linearly with the reduction of the sensor thickness, as the direct radiation load to the sensor is reduced.

The photons below 50 keV have a non-negligible probability to be absorbed in the sensor and contribute to the creation of a pixel cluster. This effect is particularly evident for increasing sensor thicknesses where the peak in the fluence at 5-8 keV is suppressed for thicknesses above 200 - 250 µm.

Backscattered Electrons

The biggest contribution to the degeneration of the resolution comes from the backscattered electrons. The thicker the sensor the softer the spectrum.



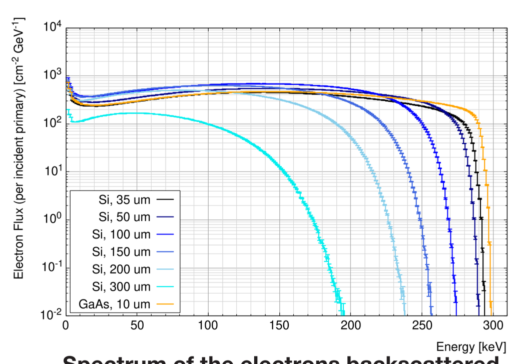
Electron backscattering flux from the VACNT layer as a function of energy and exit angle

According to **[dacunto]** and **[kyriakou]** the electron backscattered at small angles have higher probability of being channeled than those scattered at larger angles to which the material would appear amorphous.

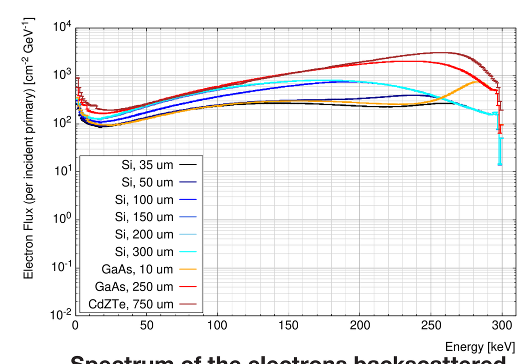
This effect as of today is not included in any of the major Monte-Carlo simulation frameworks such as Geant4 **[geant4]**, Fluka **[fluka]**, Penelope **[penelope]** and Allpix Squared **[allpix2]**, but prior works from **[cavoto]** and **[dacunto]** suggest the presence of channeling and dechanneling conditions on energy and entrance angle. Those conditions define whether or not the electron will interact with the carbon as an amorphous material or will be scattered instead along the aligned VACNTs.

The simulation could potentially be handled in Fluka by defining a special external routine that describes the interaction of the electrons with the VACNTs structure. This will be the focus of future work.

Simulations involving a high number of low energy single Coulomb interactions are very CPU intensive. We could in alternative include a modified multiple Coulomb scattering formulation that takes in account the bulk effects rather than the single interaction (properties of the specific VACNTs layer, multi walled VACNT, single walled VACNT, tree density etc.).



Spectrum of the electrons backscattered from the VACNTs



Spectrum of the electrons backscattered from the sensor

The DQE is also affected by the fraction of the primary beam which is directly bouncing off the sensor surface (with or without prior interaction). This effect is stronger for high-Z material such as CdTe or CZT although the reduction of the thickness help to minimize its effects. Although this has nothing to do with the detector substrate, it's worth mentioning that sensor thicknesses above 150 um will only have limited benefits from the mitigation of the backscattering effects introduced by the VACNTs.

Conclusions

VACNTs are a very interesting material that could be used in our detectors to reduce the material budget, granting mechanical stability, optimal thermal and electrical conductivity at the same time. The usage of VACNT would not only be limited to MAPS detectors but could also be applied to hybrid-pixel detectors.

Accurate modelling of the interaction in the VACNTs (with adequate experimental verification) is required in order to quantify their potential effect on the DQE of a detector.

We are open to discuss any possibility of collaboration with research institutes or commercial partners. Talk to us!