A Closer Look at how Research has Furthered the Development of Charged Couple Devices

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Abstract

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Introduction

In 1969, Willard S. Boyle and George E. Smith worked at Bell Laboratories on developing a new scientific instrument called a charge coupled device (CCD) which would eventually become integral detectors in many areas of scientific research (Janesick 3). The CCD was first proposed and intended to be a memory device, but it soon become clear to those at Bell Labs that there were many other applications such as helping astronomers detect and produce images of far away photons (Janesick 5). Current research has been focused on improving the design of the CCD in order to achieve lower noise to signal ratios and thus allowing CCDs to be useful in areas of research involve high precision (Tiffenberg "Sensei..."). This paper will outline the basic concepts of charged coupled devices, current limitations on the original model and how research has worked to overcome these barriers, and explore current research areas the new device can be utilized.

History of Charged Coupled Devices

In 1970, Boyle and Smith published a paper explaining the core concept of a CCD: take the less abundant charge carriers (typically these are holes or electrons) that are in a potential well (which is at the surface of a semiconductor) and move these charge carriers around by moving the potential minimum. This basic idea was achieved in three steps: 1) the charges are somehow being injected or generated at the surface or the semiconductor 2) the charge is being transferred over the surface of the semiconductor and 3) the locations and magnitude of the charges are being recorded. These steps resulted in a detector that could read out an image of the charges that were deposited or generated at the surface of the detector (Boyle 587-590).

However, in order for this type of detector to work, it is necessary to create some way to move the potential well. In the initial paper about CCDs released in 1970, Boyle and Smith talk about the idea of building an array of conductor-insulator-semiconductor capacitors and then applying the correct voltages to these conductors in order to create a CCD (Boyle 587). The key to the whole design of the CCD is that the charges should be moved across the array and detected in an easy and organized way. Figure 1 shows how Boyle and Smith describe a three stage process where the voltage is varied upon sets of three conductors. This process allows the charges to start in under an electrode and be shifted over one space by lowering and then raising the voltage. By varying the voltage through these three stages multiple times, one is able to move and register the charges over one row at a time until all charges are collected on one side of the CCD (Boyle).

[more basic info on CCD and some sort of transition]

When used to detect photons, a CCD relies on the photoelectric effect to create electron-hole pairs that can then be detected and read by the detector. Massive particles or many photos hitting the same place on the CCD will create many electron-hole pairs and are not a problem for the CCD to detect. However, a single photon will only make one or a few electron-hole pairs and this can become a problem when we factor in the fact that CCDs have noise (i.e. the sensitivity of the device would not allow us to accurately measure just one photon). The readout noise present in the CCDs have been the limiting factor for uses and precision of CCD especially when considering a device that can count a single photon (Tiffenberg).

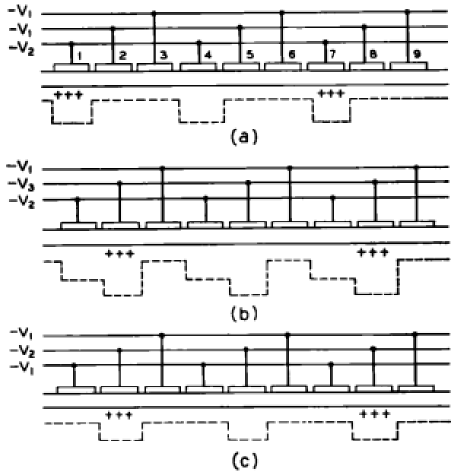

Figure 1: Schematic showing the three phases of a CCD. (a)positive charges are shown under the 1st and 7th electrode (b) charge transfers from electrode 1 to potential minimum under electrode 2 and 8 (c) charge has been fully shifted over to electrode 2 and 8 (Boyle).

Skipper CCD

In 2010, a research and development team at Fermi National Lab, dubbed "Sensei", created and tested a new device called the Skipper CCD with the aim of achieving single-electron sensitivity in the read-out noise (Tiffenberg "Sensei"). When working on the Skipper CCD, the most important aspect for the Sensei group to keep in mind was the readout noise in the output stage. This is because currently the main limitation when trying to use CCDs for detecting low signals or trying to differentiate the energy between two very similar signals is the low signal to noise ration (caused by a lot of noise during the readout). This noise is caused by electrical noise changing the pixel value during various stages in the CCD readout process such as the output amplifier, the readout system, and the bias and clock signals used to collect the charges. The readout out process is used by the CCD to recover and digitize the value of each pixel and so an addition of electronic noise is really changing the value of the collected charge and thus altering the signal seen by the detector (Fernandez).

A new technique was implemented in the Skipper CCD to reduce noise and involved using a "floating gate output stage" to repeatedly measure the charge in each pixel. This effectively lowers the noise from approximate 2e- rms/pixel to 0.068 e- rms/pixel which is appealing because this lowers the probability of the detector misreading a single photon to about 10^{-13} (Tiffenberg "Sensei"). Noise created within the output stage depends directly on the capacitance so a design with minimized capacitance will experience less noise. In the current models, the floating diffusion node has a voltage

$$\Delta V = \frac{\Delta Q}{C_J + C_{PFD} + C_{IN}}$$

where the total capacitance made up of the capacitance at the junction between the floating diffusion and the bulk (c_J), the parasitic capacitance at the node (C_{PFD}), and the capacitance of the output amplifier (C_{IN}). Through the new design, the Skipper CCD has a total capacitance that really only relies on CPFG and CIN thus reducing the read out noise (Fernandez).

The Skipper CCD was developed on a high resistivity, n-type silicon made up of 1022 by 1024 pixels that have a 15 micrometer width. These pixels are placed in four quadrants that each have an amplifier at the corner of the chip/detector. This is the first accurate single-electron counting CCD that has been tested and the first sensitive and robust equipment that can operate above liquid nitrogen temperatures. Another exciting, and important, feature of this design is that it is not adding any major modifications to the manufacturing process which means that current manufacturing facilities will be able to produce the new CCDs (and they should not be outrageously expensive compared to current CCD prices) (Tiffenberg).

[Add more info about other ways the Skipper CCD has changed to have lower readout noise]

Future Uses

In terms of scientific application of the new Skipper CCD, there are many exciting areas of particle and astrophysics that will benefit from the precision. The new Skipper CCD will allow for direct detection experiments in dark matter to have sensitivity to several different types of dark matter candidate particles (including particles with masses less than 1 MeV) and bosonic dark matter particles (Tiffenberg). The Sensei project is made up of particle theorists and experimentalists that all have the main goal of producing a new ultra-sensitive detector to search for the dark matter particles that make up 85 percent of the universe's matter. Some of these particle candidates (called hidden-sector) lie within the eV-to-GeV range of masses which has been an under-explored possibility until recently (Tiffenberg "Sensei...").

In observational astronomy, this new CCD allows observers to have low signal to noise ratios (SNR) during their exposure (while taking a photo). One particular area of interest in astrophysics would be the search for terrestrial exoplanets in the habitable zones (essentially planets that have similar conditions to earth in terms of distance from their star). These planets are expected to have a photon flux of 1 photon per several minutes which means that the sensitivity of the Skipper CCD can allow for direct space-based images and spectroscopies of earth-like planets with shorter exposure times (Tiffenberg).

Conclusion

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References

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