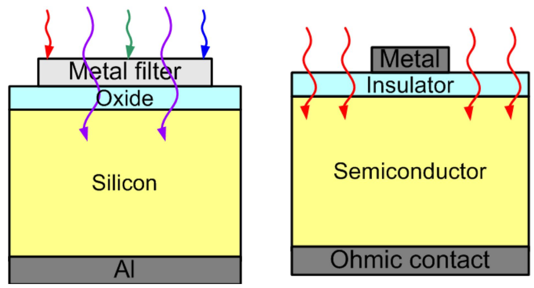
W. S. Boyle and G. E. Smith, "Charge coupled semiconductor devices," in *The Bell System Technical Journal*, vol. 49, no. 4, pp. 587-593, April 1970. Doi: 10.1002/j.1538-7305.1970.tb01790.x
URL:http://ieeexplore.ieee.org.proxy1.cl.msu.edu.proxy2.cl.msu.edu/stamp/stamp.jsp?tp=&arnumber=6768140&isnumber=6768133

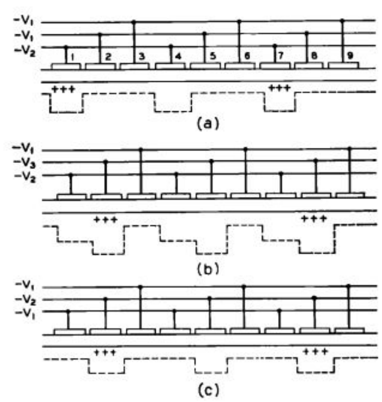
Words I had to look up while reading this paper:

- Minority carriers - the less abundant charge carrier; they can be holes or electrons depending on the type of semiconductor material or equal amounts of holes and electrons if in a semiconductor without impurities
- Semiconductor - has conductivity between an insulator and a conductor because of impurities or temperature
- MOS structure: metal-oxide-semiconductor (left)
- MIS structure: metal-insulator-semiconductor (right)



Summary of this article:

At the core of a CCD, the concept is as follows: we want to take the minorities carriers that are in a potential well (which is at the surface or a semiconductor) and move them around by moving the potential minimum. This is basically allowing for three steps to take place: 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. This creates a detector that read out an image of the charges that were deposited or generated at the surface of the detector. However, in order for this type of detector to work, it is necessary to create some way to move the potential well. This paper talks about the idea that we can build an array of conductor-insulator-semiconductor capacitors and then applying the correct voltages to these conductors.



The key to the whole design of the CCD is that the charges should be moved over and detected in an easy and organized way. The image to the right shows how the authors of the paper describe a three stage process where the voltage is varied upon sets of three conductors. This process allows the charges to start in the beginning and be shifted over one space by lowering and then raising the voltage. By varying the voltage through these three stages multiple times, you are able to move and register the charges over one row at a time.

Ways I think I will use this article:

I recognize that this article is old (from 1970) but it does a nice job explaining the concept of CCDs and how they can be used in scientific work. My paper will most likely have an introduction section which is simply an explanation of the history, uses, and design of CCDs so that the reader can be familiar with the devices. Since that is the goal of this paper, I believe that I will be using much of the information found in this paper to try to explain the physics behind a CCD.

Tiffenberg, Javier, Sofo-Haro, Miguel, Drlica-Wagner, Alex, Essig, Rouven, Guardincerri, Yann, Holland, Steve, Volansky, Tomer & Yu, Tien-Tien (2017). Single-Electron and Single-Photon Sensitivity with a Silicon Skipper CCD. *Phys. Rev. Lett., 119*, 131802. URL: https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.119.131802#fulltext

Summary of this article:
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.

The new technique that was implemented in the “Skipper CCD” to reduce the readout noise involves 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 exciting because this lowers the probability of the detector misreading a single photon to about 10^{-13} (which is super small!). 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).

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 $\gtrsim$ 1 MeV) and bosonic dark matter particles. In observational astronomy, this new CCD allows observers to have low signal to noise ratios (SNR) during their exposure (while taking a photo). This is exciting because it can allow for direct space-based images and spectroscopies of exoplanets in habitable zones (essentially planets that have similar conditions to earth in terms of distance from their star).