

How It Works: The Charged-Coupled Device, or CCD

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Courtney Peterson is the current Editor in Chief of JYI and is a third-year biology and physics major at Georgetown University. In this article, written for a non-specialized audience, she explains what a CCD is, how it works, and why it is so important.

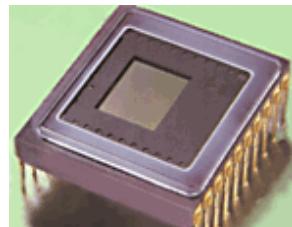
What allows us to see to the edges of the Universe, yet also lets us explore and build objects smaller than a hundredth of the width of a human hair? Here is another hint: it has revolutionized astronomy in a little over two decades, and is utilized in many imaging devices. Give up? The answer is the charge-coupled device, or the CCD.

This small, electrical device is familiar to astronomers, physicists and engineers but now even some biologists and chemists are beginning use CCDs in their research. You have likely encountered it before, as CCDs are used in facsimile machines, photocopiers, bar-code readers, closed-circuit television cameras, video cameras, regular photographic cameras, or other sorts of sensitive light detectors. In fact, CCDs have a wide range of applications - everything from reconnaissance and aerial mapping to medicine, microtechnology and astronomy.^{6,7}

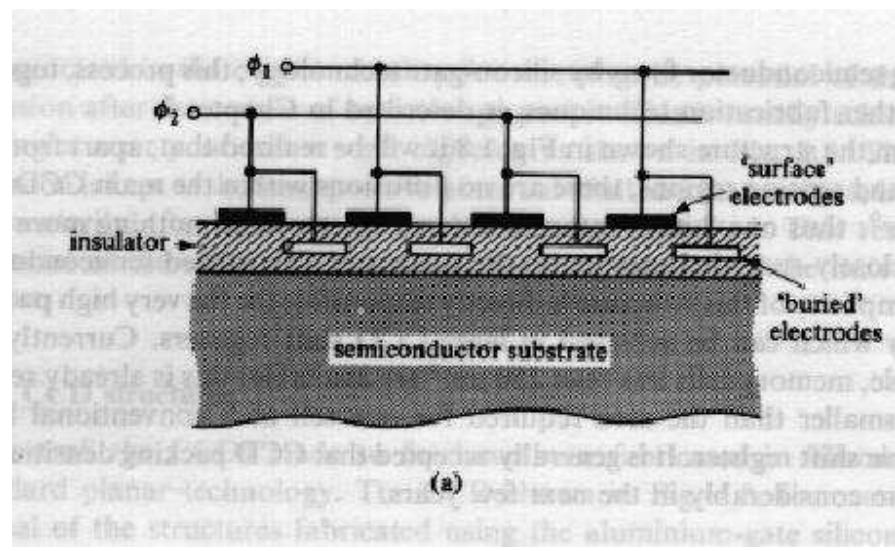
What is a CCD?

Example of a CCD Chip

A CCD is an electrical device that is used to create images of objects, store information (analogous to the way a computer stores information), or transfer electrical charge (as part of larger device). It receives as input light from an object or an electrical charge. The CCD takes this optical or electronic input and converts it into an electronic signal - the output. The electronic signal is then processed by some other equipment and/or software to either produce an image or to give the user valuable information.^{1,2}



A CCD chip is a metal oxide semiconductor (MOS) device. This means that its base, which is constructed of a material which is a good conductor under certain conditions, is topped with a layer of a metal oxide. In the case of the CCD, usually silicon is used as the base material and silicon dioxide is used as the coating. The final, top layer is also made of silicon - polysilicon.^{1,7}



This silicon that forms the base and the top layer, however, is special in nature. It is a silicon material that is doped with, or made to contain, a small amount of some other material. Doping endows materials with special properties that can be exploited through different electrical means.

To understand why doped silicon would have special properties and how those properties can be exploited, consider how silicon normally forms chemical bonds. Like carbon, a silicon atom can form up to four bonds with adjacent atoms. This is because silicon has four valence electrons that it can share to form bonds. In a crystal of pure silicon, all atoms (not on the surface of the crystal) would be perfectly bonded to four neighboring atoms; in this case, there are no extra electrons, but also no places where electrons are missing. You can see this by drawing the Lewis structures.



Lewis Diagram of Silicon's Valence Electrons



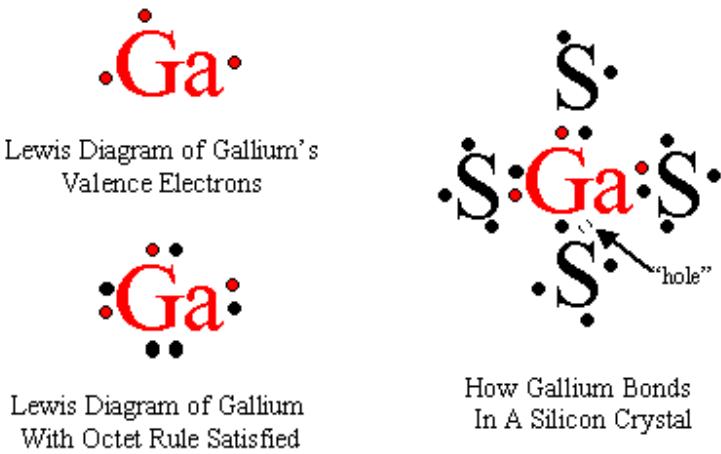
Lewis Diagram of Silicon With Octet Rule Satisfied



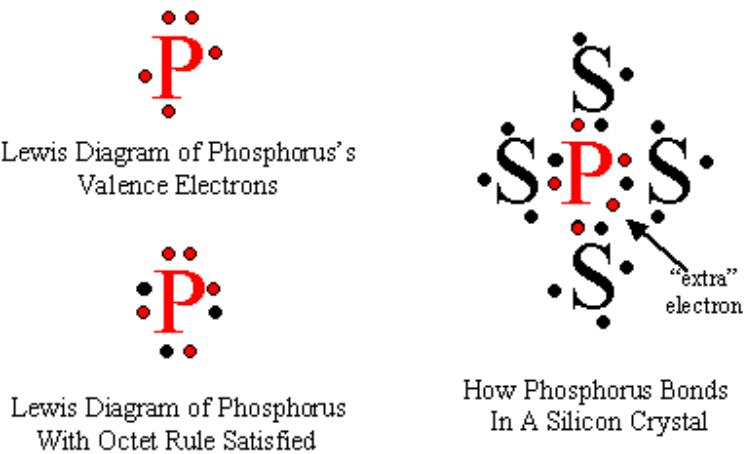
How Silicon Bonds In A Perfect Crystal

If, however, we introduce into the perfect crystal an element with only three electrons available for bonding, this atom will form three normal bonds and one

bond with a □hole□, meaning that it is missing an electron. What is interesting here is that this □hole□ actually can move around the entire crystal. An electron nearby can move to fill in the original hole, but in eliminating the original hole, it has created a new hole. Effectively, this hole is able to move around just a freely as a mobile electron. Such a material, one that contains extra holes, is called a p-type material.



A material with extra electrons is called an n-type material. In a n-type material, the □contaminating□ element has five available electrons, so it makes the four usual bonds, but then has an extra electron left over. It is important to note that these materials are all neutral, and that extra electrons or extra holes in this case do not make the materials charged but merely come from what is left over or needed for a neutral atom to form four bonds.



Upon application of the right stimulus, the movement of the hole can be directed. This is one of the fundamental keys to the operation of the CCD. An electron is repelled by negative charge and is attracted by positive charge. A hole, however, is repelled by the positive charge and is attracted by negative charge. In this way, we

can think of a hole as sort of a □positive□ electron, even though it is not. As we can control the motion of electrons by applying different electrical fields or charges in the vicinity, so can we control the motion of holes.

If a p-type and an n-type material are brought into contact, a p-n junction is formed and a very interesting result occurs. Extra electrons from the n-type material will diffuse to the p-type material and fill in some of the extra holes from the p-type material. The diffusion and recombination of electron-hole pairs across the boundary directly results in the n-type material becoming positively charged and the p-type material becoming negatively charged. Recall that before the two materials were brought into contact and before diffusion occurred, they were both neutral. As diffusion occurs and the n-type and p-type materials become increasingly charged, an electric field is generated around the contact boundary. This electric field eventually slows and stops the diffusion of charge across the boundary. When diffusion stops, there are no more extra electrons or holes around the boundary; they have all recombined. This region surrounding the boundary in which electrons and holes have recombined is called the depletion region. Outside of the depletion region, extra electrons still remain in the n-type material and extra electrons remain in the p-type material. The depletion region is the key area which can be used to create electrical devices. By applying a voltage to the depletion region, we can either increase or decrease the electric field across the depletion region. If the electric field is increased by an applied voltage (reverse bias), the depletion region is increased and less of any applied current can flow through the two materials. If the electric field is decreased by an applied voltage (forward bias), the depletion region is decreased and more applied current is allowed to flow through the two materials.

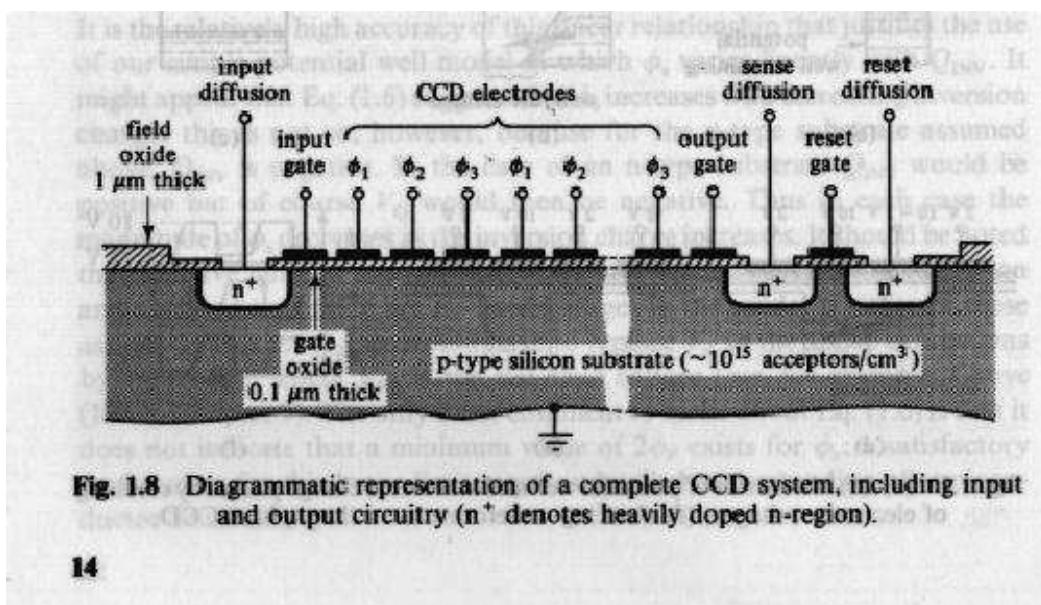
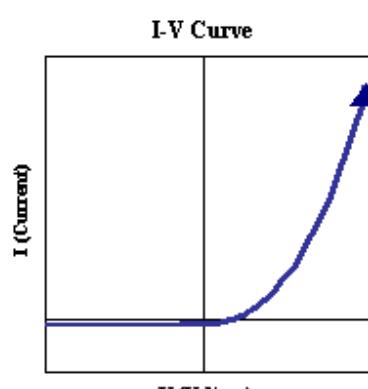


Fig. 1.8 Diagrammatic representation of a complete CCD system, including input and output circuitry (n^+ denotes heavily doped n-region).

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The importance of applying voltages to the depletion region (called biasing the p-n junction) is that it precisely allows us to control applied current through any p-n material. When the p-n junction is reversed-biased, an only infinitesimal amount of applied current can flow, which for all practical purposes is zero. This corresponds to the □off□ state. When the p-n junction is forward-biased, current easily flows through the junction (because the smaller electric field does not impede the flow of charges as much). In fact, by plotting a graph of applied voltage



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