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Schottky junction solar cells

A photovoltaic cell can be created from the Schottky junction between a semiconductor and a metal, with or without an insulating layer between them. Solar cells of this type have a long history, dating back to 1883, when Charles Fritts coated selenium with a thin layer of gold to make one of the world's first solar cells. However, since then, they have commanded only a small amount of attention from researchers and corporations; no popular solar-cell design uses metals in the active region, other than for contacts. Nevertheless, in the past decade or two, university research and an industrial pilot production line have demonstrated the potential commercial viability of one particular Schottky junction solar cell design, the silicon "MIS-IL solar cell" (short for metal-insulator-semiconductor inversion-layer), and moreover they continue to be used fairly commonly in a lab setting (due to their simple architecture). In this paper, we will examine the general operating principles of Schottky junction solar cells, with particularly emphasis on the MIS-IL design of primary commercial interest.

1 Background on Schottky barriers

As discussed in class, an interface between a metal and semiconductor can induce a depletion or inversion layer in the semiconductor. (It can also induce an accumulation layer, but this case is not of interest for this paper.) A built-in potential called the "Schottky barrier" appears between the bulk of the semiconductor and the surface. The magnitude of the potential is called the "Schottky barrier height" (SBH). As discussed in class, for a perfect abrupt junction between the metal and semiconductor, the Schottky-Mott model gives the SBH in terms of the electron affinity of the semiconductor, the work-function of the metal, and the band gap. For a p-type semiconductor,

$$\text{SBH} = (\text{band gap}) + (\text{electron affinity}) - (\text{work function})$$

while for an n-type semiconductor,

$$\text{SBH} = (\text{work function}) - (\text{electron affinity})$$

In reality, however, the SBH is not described well by the Schottky-Mott model, because of interface states and defects.

Similar to this is the MIS (metal-insulator-semiconductor) junction, wherein a thin insulator (a few nanometers, typically) is inserted between the metal and semiconductor. The insulator functions as a tunnel barrier, allowing electrons and holes to tunnel through with some finite probability. In the Schottky-Mott model, the insulator lowers the barrier height very slightly, because some of the electric field drop occurs across the insulator, rather than between the surface of the semiconductor and the bulk. However, since the insulating layer tends to be much thinner than the depletion region, the potential drop is small and the effect is negligible. Experimentally, on the other hand, the SBH is often significantly larger in an MIS than in the analogous MS structure, contrary to the Schottky-Mott model.[1]

2 IV characteristics

Across an MS or MIS barrier, there are two types of current paths. In the "minority carrier current path", a minority carrier passes between the metal and the semiconductor (through the insulator, if there is one). The "majority carrier current path" is analogous.

2.1 Minority carrier current path

The minority carrier current path is essentially the same as in a p-n junction, but instead of achieving the junction through a change in doping, you achieve it through the inversion or depletion layer induced by the metal. As always, the current goes in both directions. In the reverse direction, there is a generation current from electron-hole pairs generated in or near the depletion region either thermally (in the dark) or from photons (in the light). In the forward direction, there is the recombination current from majority carriers diffusing into the depletion region, then recombining. The net dark current, as with a normal p-n junction, is

$$I = I_{0,minority} (Exp(eV/kT)-1).$$

2.2 Majority carrier current path

The majority carrier current path is not present in a p-n junction. Here, the majority carrier from the bulk semiconductor goes to or from the metal, without ever involving minority carriers.

The main contribution to reverse dark current (majority carriers moving from the metal to the semiconductor) is Schottky-Richardson emission (also called "Thermionic emission"). Here, the carriers in the metal randomly have enough energy to pass over the barrier height. The magnitude of this current is reasonably constant with respect to applied voltage, since the energy barrier from the metal to the semiconductor is reasonably constant, unlike the energy barrier from the semiconductor to the metal, which reduces markedly in forward bias.

The constant reverse-current is balanced by a forward current consisting of majority carriers being thermally excited over the Schottky barrier. On net, we get the classic diode equation:

$$I = I_{0,majority} (Exp(eV/kT)-1).$$

Note that this is a somewhat simplified picture. The full electrostatics of the MIS system, including image-charge lowering,[2] field emission,[2] interface-state dynamics, and so forth, means it does not satisfy the classic diode equation, but rather can have large ideality factors, non-saturating reverse current, and other complications.[3,4]

2.3 Effect on solar-cell performance

Summed up, we get a typical diode characteristic, with saturation current $I_0=I_{0,minority}+I_{0,majority}$. High saturation current hurts solar-cell performance, and therefore the "extra" majority-carrier current path is detrimental to the net efficiency. This is the main justification for inserting an insulating layer: A tunnel barrier of the correct thickness (typically a few nanometers) can reduce $I_{0,majority}$, without appreciably lowering the short-circuit current, which involves minority carriers tunneling through the insulator. The reason for the asymmetry is that the electric field drives the minority carriers towards the barrier, where they can pile up to a certain degree while waiting to tunnel through. The majority carriers, on the other hand, are being driven away from the interface by the electric field, so slowing their passage can dramatically reduce their net flow.[5]

3 MIS-IL Cells

The most important realization of Schottky barrier solar cells today is the "MIS-IL solar cell," made from single-crystalline (SC) silicon. The processing sequence for a standard (or "first-generation") MIS-IL solar cell is as follows:[6,7] First, the top surface is textured mechanically and chemically. Second, the back aluminum contact is evaporated on. Third, there is a heating stage, which simultaneously sinters the Al and grows a 1.5nm SiO_2 thermal oxide. Fourth, the front aluminum grid is mask-evaporated. Finally, the structure is dipped in CsCl, and then a SiN_x layer is deposited on the front side by PECVD. The SiN_x layer passivates the surface, reducing recombination, functions as an antireflective coating, and moreover its interface states and charges are such that it creates an inversion layer in the silicon. The CsCl dip incorporates Cs^+ ions, increasing the density of positive charges in the SiN_x, and hence the strength (and therefore conductivity) of the inversion layer.[8]

One key difference with the standard solar-cell process is the lack of a high-temperature phosphorus-diffusion step, which ordinarily creates the n-layer of the p-n junction. The elimination of this step is advantageous for two reasons: First, the energy input into the solar-cell production process is 35% lower,[9] which lowers production cost and the energy-payback-period for the cell. Second, the crystal defects and high doping of the diffused layer tends to increase saturation current due to SRH and Auger recombination, respectively. Lacking this layer, the MIS-IL cell can achieve a larger-than-usual open-circuit voltage, as high as 655 mV in SC-silicon in an early 1979 cell.[10] On the other hand, while the lack of the diffusion step is an advantage of MIS-IL cells on high-quality SC-silicon, it is a disadvantage on low-quality Si, since there the high-temperature diffusion step improves crystal quality by gettering impurities.

4 Commercial Status and Prospects

From 1994, >1 MW_p of "first-generation" MIS-IL cells were manufactured in an industrial pilot plant.[9] These cells showed an efficiency of 15.3% for 10x10cm^2 CZ-Si crystals, and 15.7% for 2x2cm^2 FZ-Si. However, ongoing research has uncovered substantial room for improvement in the process. The best current approach is "OECO-MIS-IL" solar cells.[11] (OECO stands for "obliquely evaporated contacts".) The key advantages of this technique are, first, the mask-evaporation step, which was found to be difficult to scale up, is eliminated, being replaced by the OECO metal-grid-deposition technique; and second, the SiN_x passivation layer can be deposited at a higher temperature, creating better passivation. (In a first-generation MIS-IL cell, increasing the SiN_x deposition temperature would degrade the MIS contacts; in the new processing sequence, the metal is deposited *after* the SiN_x.) These cells have 19.6% record efficiency. This efficiency is for a lab cell, but it is claimed that it was created using only cheap, industrially-scaleable processes, and moreover with much room for further improvement.

In conclusion, MIS-IL solar cells are a promising candidate for the future of high-end SC-Si solar cells, offering distinct advantages in cost and efficiency. However, one should keep in mind that there are a large number of new, innovative, and advantageous SC-Si solar cell architectures, and it is beyond the scope of this paper to state where MIS-IL solar cells stand among all the great contenders in today's marketplace. Nevertheless, it will be exciting to see the results of this research effort, which continues both in the laboratory and in pilot plants.

References:

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