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Diffusion Techniques, From Blue-Cell Theory To In-Fab Practice

Cell manufacturers can increase final product efficiency by incorporating new breakthroughs into the diffusion process.

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Scientifically speaking, a solar cell is a device that converts solar energy into electric power without thermal or mechanical hardware. It is the photovoltaic effect (Einstein's theory) that a photon of right energy absorbed by a semiconducting material creates a pair of electrons and its counterpart, a hole. The electron, which is negatively charged, and a hole, which is positively charged, travel in opposite directions.


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Among all solar cell devices, the most commonly used material is silicon, which is one of the most abundant elements on Earth. Intrinsically, silicon is a non-conducting material, meaning that it does not conduct electrical current because of its wide energy band gap.

During material preparation, a dopant is introduced homogeneously into the silicon lattice to make it electrically semiconducting, meaning that it conducts electricity in only one direction, according to the type of dopant added.

The most common dopants are phosphorus and boron. When a silicon lattice is doped with phosphorus, the electric conduction is dominated by electrons and called N-type. Boron-doped silicon is dominated by holes and is called P-type.

After the material is prepared in this way, an electrical junction must be formed by thermal diffusion of oppositely charged impurity. This is the most critical process in cell preparation. A junction is formed on the N-type substrate by boron diffusion on the front, known as the emitter.

Likewise, a P-type substrate is diffused with phosphorus atoms. The junction provides a built-in voltage that separates the electron-hole pairs that flow through an external circuit. The N-diffused emitter side is similar to the negative terminal of a battery, and the base material on the back is the positive terminal. Alternatively, the diffused boron emitter side can serve as the positive terminal, and the base can work as the negative terminal.

Today, nearly 80% of silicon solar cells - whether monocrystalline cells or polycrystalline cells - are made from P-type (boron-doped) starting material. Reasons for the choice include easier material preparation of boron-doped ingots and that the subsequent phosphorus diffusion requires a lower temperature.

Diffusion processing

Traditionally, silicon solar cell diffusion uses adapted processes that were previously well developed by the semiconductor industries. An oxychlorophosphate compound is heated into vapor and introduced into a quartz tube, in which silicon wafers are placed at temperature as high as 875 degrees C.

The phosphoric compound reacts with the silicon oxide on the substrate's surface to release phosphorus that diffuses into the wafer. The process occurs in true vapor form, and the diffusion follows Fick's equation of solid diffusion (see Figure 1):

Figure 1

$$\frac{\partial C(x,t)}{\partial t} = D \frac{\partial^2 C(x,t)}{\partial^2 x}$$

(where *C* is impurity concentration, *D* is diffusion coefficient, and *x* and *t* are space and time, respectively)

Source: BTU International

One load contains approximately 250 wafers, and the whole diffusion cycle - including heat-up and cool-down - takes approximately 30 minutes. In general, the junction characteristics prepared in this way are ideal as theoretical prediction. The drawbacks of this batch-mode diffusion process, however, include a long process time, limitations in wafer dimensions and a toxic dopant precursor with the emission of chlorine gas.

In the early 1980s, a direct coating of phosphoric acid onto wafers was successfully tested at Solarex. At 14%, cell efficiency using this continuous in-line diffusion technique almost matched that of tube diffusion. Cost reduction in dopant material, together with much higher throughput by equipment automation, cut costs per watt by over 50%.

However, cell efficiency remained limited due to unnecessarily deep junction formation - a hereditary diode concept from the semiconductor industry. Although a diode must be very low in leakage current at very high breakdown voltage - meaning that the junction must be deep with heavy doping level in the diffused layer - a solar cell depends on light transparency with very low to no carrier recombination in the junction vicinity.

A deep junction with heavy dopant level in the diffused layer yields ideal diode characteristics, but it also absorbs blue light of high energy in the sunlight. The blue light absorbed by the diffused layer is converted into heat instead of electrical currents, causing a double loss to the cell efficiency.

The goal of a blue cell is to reduce the diffused layer to as thin as possible - just enough to form a junction without the presence of a dead layer. This step calls for a shallow diffusion, which is the opposite of the deep junctions found in bipolar applications.

Shallow-junction devices also show a lower surface recombination than is found with other techniques. This is another factor for cell improvement. A further decrease in surface recombination was achieved through the use of plasmatic hydrogen passivation, a byproduct of plasma-enhanced chemical vapor deposition processes. Overall, through the use of the blue-cell concept and hydrogen passivation, cell efficiency has been improved to over 16.5%.

Further processing improvements

The blue-cell concept has a long history and is currently being implemented in applications where solar cells are used in space. The grid lines, or figures on the emitter surface, are formed by metal vapor deposition with photo-lithographic techniques. Cell efficiency has been over 18%, but this process has proven expensive and slow.

To date, front contacts for terrestrial solar are almost exclusively processed by silver paste screen printing and alloyed in an open infrared belt furnace. However, paste firing requires a certain junction depth. The minimum is generally 0.2 microns. Below this number, the metallic paste may puncture the junction, causing shunting. Consequently, blue cells cannot easily be processed with paste printing.

The shunting problem, however, may be solved by using an advanced cell device in which areas under the paste fingers (or grid lines) are selectively doped much more heavily than the rest of the open surface area. The heavily doped area prevents shunting and promotes an ohmic contact condition for current collection.

In addition, selective-emitter (SE) processing has proven to increase solar cell efficiency to over 18.5%. One of the simplest SE processes commonly used today is to incorporate advanced laser technology. A light-diffused wafer is coated with the phosphoric compound in a coater, and a laser beam (e.g., Nd:YD) with no larger than a 60-micron focal spot is programmed to anneal only the grid-line area.

The wafer is then aligned with a printer for paste printing at the annealed area, followed by infrared firing. The cell prepared in this way has excellent short wavelength response with low series resistance, without shunting.

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A solar cell's performance depends on light absorption, which is a function of active surface area or inversely proportional to the shadowing factor by the grid lines. With laser processing, the minimum shadow factor has been about 5% to date.

Straight calculation shows that the cell performance would be over 19% by eliminating the shadow factor altogether. Doing so would be possible if all the gridlines and busbars were made on the back of the cell, leaving the front entirely clear for exposure.

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