Some applications of photovoltaic cells that have been well established over the past 50 years include:

1. Supplying power in remote locations, e.g. for communications and weather monitoring systems and the lighting and water pumping systems used in developing countries;
2. Supplying power for consumer products, e.g. for electronic calculators and garden lights; and
3. Supplying power for applications in space, e.g. for satellites and space vehicles.

Most photovoltaic cells produced are currently deployed for large-scale power generation either in centralized power stations or in the form of ‘building integrated photovoltaics’ (BIPV). BIPV is receiving much attention, as using photovoltaic cells in this way minimizes land use and offsets the high cost of manufacture by the cells (or panels of cells) acting as building materials. Although crystalline Si solar cells were the dominant cell type used through most of the latter half of the last century, other cell types have been developed that compete either in terms of reduced cost of production (solar cells based on the use of multicrystalline Si or Si ribbon, and the thin-film cells based on the use of amorphous Si, CdTe, or CIGS) or in terms of improved efficiencies (solar cells based on the use of the III-V compounds).

All of these semiconductors have energy bandgaps within the range 1.1-1.7 eV, that is they are near to the optimum energy bandgap (1.5 eV) for photovoltaic solar energy conversion by a single junction solar cell. The best efficiencies obtained with each cell type are given in Table 1 and the market share of the different cell types during 2006 are given in Fig. 1. Although the use of crystalline Si cells has continued to increase rapidly, the most successful technology at present is that based on the use of multicrystalline Si, which has expanded even faster. The key aim of all the technologies is to reduce production costs to 1 $/peak Watt (1 $/Wp) to compete on cost with other forms of power generation. Cells based on the use of crystalline and multicrystalline Si cost more than four times this amount. It is generally accepted that this target is most likely to be reached using thin-film fabrication technologies when expanded for large scale production. The technologies also need to have acceptable energy payback times – this is the time taken for a device to generate as much energy as was needed to fabricate the device. Crystalline
and multicrystalline devices typically have energy payback times of 3–4 years and the thin-film technologies, 12–18 months. Fig. 2 shows two examples of BIPV, the first using crystalline Si solar cells, the second using CIGS thin-film solar cells.

### Si-based cells

**Crystalline Si solar cells**

A cross-sectional view of the Si solar cell structure that has been used in production up to the present is given in Fig. 3a. For crystalline Si devices, a boule of B-doped p-type Si is grown using the Czochralski method and wafers are sawn from the boule. Crystalline (and multicrystalline) Si have an indirect energy bandgap resulting in a low optical absorption coefficient, with the consequence that the wafers need to be greater than 200 µm thick to absorb most of the incident light. The wafer surfaces are ‘textured’ by dipping into a solution of NaOH and isopropyl alcohol to minimize reflection losses and to refract light entering the Si to high angles of refraction and enhance the optical path length in the Si. A p-n junction is formed by diffusing phosphorus into the wafer as an impurity dopant. Screen-printed Ag contact fingers are used on the n-type surface to make electrical connections to the p-type material.
Inorganic photovoltaic cells

Inorganic photovoltaic cells are an alternative to their silicon-based counterparts. They can be made from a variety of materials, such as cadmium sulphide, cadmium telluride, copper indium gallium diselenide, or copper indium gallium selenide. The cells contain a p-n junction, which is formed by combining layers of two different types of doped silicon (p-type and n-type).

The front of the cell contains a light Absorbing layer, usually made from a thin film of copper indium gallium diselenide or sulphide. This layer allows light to pass through and interact with the cell's p-n junction to generate electricity. The back of the cell includes a back reflector and a back metal contact, which helps to ensure that the light is efficiently converted into electricity. These reflectors can be made from materials like aluminium or copper.

Typically, the front of the cell is covered with a conductive layer of silver or copper, which forms the grid that connects the p-n junctions. This layer is often screen-printed onto the surface of the cell. The back of the cell may also have a conductive layer to form the back contact, which is used to connect the cell to a power grid or battery storage system.

In some cases, the contacts are defined using photolithography or laser scribing, which can result in higher efficiencies but also increased costs. The use of photolithography and laser scribing can result in a higher efficiency of up to 14%, and the researchers at the University of New South Wales have developed such solar cells.

The highest efficiency Si solar cell produced in the laboratory is the 'passivated emitter rear locally diffused' (PERL) solar cell, which has an efficiency of 24.7%.

There is worldwide effort to minimize Si usage and design devices that incorporate ‘light trapping’ features such that thinner layers of Si can be used. One strategy is to deploy Si solar cells in ‘concentrator systems’. In these systems, a large area lens focuses the incident sunlight onto a cell with smaller area. However, with such systems, there is a need to track the sun, and concentrator systems can only be used in parts of the world where there is unimpeded sunlight. A schematic of such a system is given in Fig. 5.
Multicrystalline Si solar cells

Here, molten Si is poured into a container and then allowed to cool, resulting in Si ingots with large columnar grains (typically 0.3 mm diameter) growing from the bottom of the container upwards. The grains are so large that they extend through the wafers cut from the solidified block. The incorporation of hydrogen during device processing plays an important role in passivating the grain boundaries in the devices formed. This is most conveniently introduced by using plasma-enhanced chemical vapor deposition (PECVD) to deposit silicon nitride as the top insulating layer, rather than SiO₂, as hydrogen is used in this process. Otherwise, cell processing is similar to that used for crystalline devices. A photograph of a multicrystalline cell is shown in Fig. 4b. Advantages of using multicrystalline growth over the Czochralski method include lower capital costs, higher throughput, less sensitivity to the quality of the Si feedstock used, and higher packing density of cells to make a module because of the square or rectangular shape of the cells. The best modules made using multicrystalline Si generally have efficiencies 2–3% less than those of crystalline Si, and cost approximately 80% of crystalline Si cells to produce.

It is also possible to pull multicrystalline Si in the form of thin sheets or ‘Si ribbon’ from a Si melt, and the sheets then processed to make solar cells. The need for sawing wafers can be avoided using this method. However, because resulting cells generally have lower efficiencies than those made from the cast blocks and the casting method is simpler, the casting method is preferred by most manufacturers.

Amorphous Si solar cells

Thin films of amorphous Si are usually produced using PECVD of gases containing silane (SiH₄). The layers may be deposited onto both rigid substrates (e.g. glass) and flexible substrates (e.g. thin metallic sheets and plastics), allowing for continuous production and diversity of use. The material used in solar cells is actually hydrogenated amorphous Si (α-Si:H), an alloy of Si and hydrogen (5–20 at. % H), in which the hydrogen plays an important role of passivating the dangling bonds that result from the random arrangement of the Si atoms. The hydrogenated amorphous Si is found to have a direct optical energy bandgap of 1.7 eV and an optical absorption coefficient, α, greater than 10⁵ cm⁻¹ for photons with energies greater than the energy bandgap. This means that only a few microns of material are needed to absorb most of the incident light, reducing materials usage and hence cost. Most devices produced have the p-i-n structure shown in Fig. 6a. A major problem with modules made using single p-i-n junctions is that...
the efficiency degrades under illumination to less than 5% because of a phenomenon known as the Staebler-Wronski effect\(^29\).

It is possible to absorb the solar spectrum more efficiently and to improve cell stability by using multiple \(p-i-n\) structures with different energy bandgap \(i\)-layers to produce 'double junction' or 'triple junction' structures as shown in Figs. 6b and 6c. Narrower energy bandgap layers are produced by alloying the Si with Ge and wider energy bandgap layers are produced by alloying the Si with carbon. The highest reported stabilized efficiency of a double-junction is greater than 9.5%, and for a triple-junction module it is greater than 10%\(^29\).

If the gases used for deposition of amorphous Si are diluted in hydrogen, the deposit consists of regions of crystalline Si immersed in an amorphous matrix\(^30\). This two phase material is known as 'microcrystalline Si' or sometimes as 'nanocrystalline Si'. The physical properties of the material resemble those of crystalline/multicrystalline Si rather than amorphous Si, especially with regard to stability under intense illumination. Work is currently underway to develop hybrid amorphous Si/microcrystalline Si tandem solar cells and modules (referred to in the literature as 'micro-morph devices'). Trials indicate that these hybrid devices and modules rival triple-junction amorphous Si in terms of efficiency and stability\(^31\).

**HIT solar cells**

A novel device developed by Sanyo is the 'heterojunction with intrinsic thin layer' (HIT) solar cell\(^9\). In this device, layers of amorphous Si are deposited onto both faces of a textured wafer of single-crystal Si. This results in 10 cm x 10 cm multijunction devices with efficiencies greater than 21% and 80 cm x 120 cm modules with efficiencies up to 17.3%\(^9\). The advantages of this structure include the potential for high efficiency, very good surface passivation, low-temperature processing (all steps are carried out at less than 200°C, except for substrate production), reduced energy payback time, and reduced cost relative to conventional Si devices.

**III-V solar cells**

**Single junction III-V solar cells**

The III-V compounds, such as GaAs, InP, and GaSb, have direct energy bandgaps, high optical absorption coefficients, and good values of minority carrier lifetimes and mobilities (in highly pure, single-crystalline material). This makes them excellent materials for high-efficiency solar cells\(^32\). The III-V materials used most widely for making single-junction solar cells are GaAs and InP, as both have near optimum energy bandgaps of 1.4 eV. Originally, devices were formed by the diffusion of \(n\)-type dopants into wafers from single crystals produced using either the liquid-encapsulated Czochralski (LEC) method or a Bridgmann method\(^33\). However, the highest conversion efficiencies confirmed under standard conditions are 25.8% for GaAs and 21.9% for InP single-junction cells, and were obtained with epitaxially grown homojunction structures produced in the US by the Kopin (Bedford, MA)\(^10\) and Spire (Westboro, MA)\(^11\) Corporations, respectively.

The disadvantage of using III-V compounds in photovoltaic devices is the very high cost of producing device-quality substrates or epitaxial layers of these compounds. Crystal imperfections, including unwanted impurities, severely reduce device efficiencies and alternative, lower...
cost deposition methods cannot be used. These materials are also easily cleaved and are significantly mechanically weaker than Si. The high density of the materials is also a disadvantage, in terms of weight, unless very thin cells can be produced to take advantage of their high absorption coefficients. These drawbacks have led to III-V compounds not being considered as promising materials for single-junction, terrestrial solar cells. The development of III-V based devices has been undertaken primarily because of their potential for space applications. There, the potential for high conversion efficiencies together with radiation resistance in the demanding environment of space power generation mitigates against the high materials cost. The high cost of cell manufacture can also be offset for terrestrial applications by using the high efficiency III-V cells in concentrator systems. These devices are of course subject to the requirements for direct sunlight and tracking as mentioned on page 22.

A recent development is that of quantum well (QW) cells made using GaAs and III-V alloys. A strain balanced, 50 QW solar cell has a higher efficiency than a p-n-GaAs control cell. This device was grown by metal-organic chemical vapor deposition (MOCVD). III-V multijunction devices

In a single-junction Si solar cell, 56% of the available energy is lost because photons with energies less than the bandgap are not absorbed, and photons with energies greater than the bandgap ‘thermalize’, such that the excess energy over the bandgap is lost as heat. A range of studies have shown that using multijunction solar cells (sometimes referred to as tandem solar cells), such losses can be minimized leading to much higher efficiency devices. A landmark achievement demonstrating this concept was the development in 1990 of a GaAs/GaSb stacked cell with an efficiency greater than 30%. Much work since then has been on the development of stacked cells grown by MOCVD onto GaAs, InP, and more recently Ge substrates. The most efficient stacked cell devices are now produced by Spectrolab in Sylmar, California. A cross-sectional view of a device with an efficiency >39% is given in Fig. 7.

Thin-film solar cells based on compound semiconductors

Solar cells based on CdTe

With a direct optical energy bandgap of 1.5 eV and high optical absorption coefficient for photons with energies greater than 1.5 eV, only a few microns of CdTe are needed to absorb most of the incident light. Because only thin layers are needed, material costs are minimized, and because a short minority diffusion length (a few microns) is adequate, expensive materials processing can be avoided. A cross-sectional view of a typical CdS/CdTe solar cell is shown in Fig. 8a. A front contact is provided by depositing a transparent conductive oxide (TCO) onto the glass substrate. The TCO layer has a high optical transparency in the visible and near-infrared regions and high n-type conductivity. This is followed by the deposition of a CdS window layer, the CdTe absorber layer, and finally the back contact. For commercial devices, the CdS layer is usually deposited using either closed-space sublimation (CSS) or chemical bath deposition, although other methods have been used to investigate the fundamental properties of devices in the research laboratory. The CdTe p-type absorber layer, 3–10 µm thick, can be deposited using a variety of techniques including physical vapor deposition (PVD), CSS, electrodeposition, and spray pyrolysis. To produce the most efficient devices, an activation process is required in the presence of CdCl₂ regardless of the deposition technique. This treatment is known to recrystallize the CdTe layer, passivate grain boundaries, and promote interdiffusion of the CdS and CdTe at the interface. Forming an ohmic contact to CdTe is difficult because the work function of CdTe is higher than all metals. This can be overcome by creating a thin p⁺ layer by etching the surface in bromine methanol or HNO₃/H₃PO₄ acid solution and depositing Cu-Au alloy or ZnTe:Cu. This creates a thin, highly doped region that carriers can tunnel through. However, Cu is a strong diffuser in CdTe and causes the performances to degrade with time. Another approach is to use a very low bandgap material, e.g. Sb₂Te₃, followed by Mo or W. This technique does not require a surface etch and the device performance does not degrade with time.

The most efficient CdTe/CdS solar cells (efficiencies up to 16.5%) have been produced using a slightly different design to that shown in Fig. 8a. The improved efficiency is a result of the use of a CdS SnO₂ TCO layer which is more transmissive and conductive than the classical SnO₂-based TCOs, and the inclusion of a Zn₂SnO₄ buffer layer which improves the quality of the device interface. Two companies currently manufacture CdTe-based modules: First Solar and Antec Solar. Both use
thermal sublimation processes and have managed to produce modules with baseline efficiencies of 8–9%. First Solar current production costs are $1.25/Wp for a 99 MWp/year manufacturing line, and projected output is 275 MWp/year for 2008 with estimated cost below the $1/Wp barrier. In August 2007, CdTe modules manufactured by First Solar were installed on the roof of a logistics center in Ramstein, Germany. The installation is capable of generating 2.5 MWp of power, i.e. it is currently the largest thin-film BIPV generation project using thin-film solar cells.

Solar cells based on chalcopyrite compounds
The first chalcopyrite solar cells developed were based on the use of CuInSe$_2$ (CIS). It was, however, rapidly realized that incorporating Ga to produce the solid solution Cu(In,Ga)Se$_2$ (CIGS), results in a widening of the energy bandgap to 1.3 eV and an improvement in material quality, resulting in solar cells with enhanced efficiencies. CIGS has a direct energy bandgap and high optical absorption coefficient for photons with energies greater than the bandgap, such that only a few microns of material are needed to absorb most of the incident light, with consequent reductions in material and production costs. The best CIGS solar cells are grown on sodalime glass in the sequence: back contact, absorber layer, window layer, buffer layer, TCO, and then the top contact grid. A typical structure is shown in Fig. 8b. CIGS solar cells have been produced with efficiencies of 19.5% and modules with efficiencies of 13.4%. The back contact is a thin film of Mo deposited by magnetron sputtering, typically 500–1000 nm thick. The CIGS absorber layer is formed mainly by (i) the coevaporation of the elements either uniformly deposited or using the so-called three-stage process, or (ii) the deposition of the metallic precursor layers followed by selenization and/or sulfidization. Coevaporation yields devices with the highest performance while the latter deposition process is preferred for large-scale production. Both techniques require a processing temperature >500°C to enhance grain growth and recrystallization. Another requirement is the presence of Na, either directly from the glass substrate or introduced chemically by evaporation of a Na compound. The primary effects of Na introduction are grain growth, passivation of grain boundaries, and a decrease in the absorber layer resistivity. This usually yields an increase of 1–2% in efficiency for Na concentrations <1%. The junction is usually formed by the chemical bath deposition of a thin (50–80 nm) window layer. CdS has been found to be the best material, but alternatives such as ZnS, ZnSe, In$_2$S$_3$, (Zn,In)Se, Zn(O,S), and MgZnO can also be used. The buffer layer can be deposited by chemical bath deposition, sputtering, chemical vapor deposition, or evaporation, but the highest efficiencies have been achieved when using a wet process as a result of the presence of Cd$^{2+}$ ions. A 50 nm intrinsic ZnO buffer layer is then deposited and acts as to prevent any shunts. The TCO layer is usually ZnO:Al 0.5–1.5 µm. The cell is finally completed by depositing a metal grid contact Ni/Al for current collection. The main CIGS manufacturers are Würth Solar, Avancis (formerly Shell Solar), and Global Solar. Numerous other ventures are engaged worldwide in the development of CIGS-based photovoltaic products.

Conclusions
Most commercially produced solar cells are manufactured using either crystalline or multicrystalline Si. Thin-film solar cells based on the use of Si, CdTe, and CIGS are now being mass manufactured and it is expected with economies of scale that they will achieve the cost reduction needed to compete directly with the other forms of energy production. Multijunction solar cells, so far made primarily using the III-V compounds, have clearly proven that by minimizing thermalization and transmission losses, very large improvements in efficiency can be made over those of single-junction cells. These devices find application...
in generating power for space applications and are used in concentrator systems. The future development of multijunction devices using low-cost thin-film technologies is especially promising for producing more efficient and yet inexpensive devices. Cost reductions will also be significant when the thin-film technologies are directly produced on building materials other than glass, as many materials, e.g. tiles and bricks, can be substantially cheaper than glass and have much lower energy contents.

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