Plasmonic solar cells (SCs) have great potential to drive down the cost of solar power. To make SCs a viable energy source, trapping of light is crucial for thin film SCs. So, plasmonic nanoparticles could be used to increase the efficiency of thin film SCs.

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A solar cell (SC) is a device that converts sunlight energy directly into electricity by the photovoltaic effect. Photovoltaics have the potential to make a large contribution for solving the problem of climate change and hence, require highly efficient solar cells. SCs can be divided into three different generations. The first generation SCs are made from crystalline semiconductor wafers, typically silicon with a thickness of 200-300μm. Currently 90 per cent of the solar cell market is based on first generation SCs and around 40 per cent of the cost of a solar module is due to thick silicon wafers. Second generation SCs based on thin film technology have thickness usually in the range 1-2μm, deposited on cheap substrates such as glass, plastic or stainless steel. These SCs focus on lowering the amount of material used as well as increasing the energy production. They are made from a variety of semiconductors including cadmium telluride and copper indium diselenide, as well as amorphous and...
polycrystalline silicon. A major limitation in thin film SCs technology is their ineffective absorbance near bandgap, in particular for the indirect bandgap semiconductor silicon. Therefore, it is very important to trap light inside the SC in order to increase the absorbance. Third generation SCs are currently being researched with the goal to increase the efficiency using second generation SCs. They are envisaging to improve absorption and hence efficiency by increasing the light trapping of desired frequency. A part of third generation SCs that has emerged recently is the use of scattering from noble metal nanoparticles excited at their localized surface plasmon resonance (LSPR) which is discussed here in detail.

**BASIC PRINCIPLES**

When a photon hits a semi-conductor, one of three things can happen: (i) The photon (lower than Si band gap energy) can pass through the material; (ii) The photon can reflect off the surface and (iii) The photon (higher than Si band gap energy) can be absorbed by the silicon.

When a photon is absorbed, its energy is given to an electron in the crystal lattice. Usually, this electron is in the valence band and is tightly bound in covalent bonds with neighbouring atoms and hence, unable to move far. The energy given to it by the photon “excites” it into the conduction band, where it is free to move within the semiconductor and hence, deficiency of one electron called “hole” is created. The presence of a missing covalent bond allows the bonded electrons of neighbouring atoms to move into the “hole” leaving another hole behind, and in this way a hole can move through the lattice. Thus, it can be said that photons absorbed in the semiconductor create mobile electron-hole pairs. Once the electrons and holes are separated, they need to recombine, since they are of opposite charge. The SCs are pretty efficient if the electrons can be collected before this happens. The way to collect the electrons quickly would be to make the conducting material very thin. If the surface is made very thin, there will be less light absorbed by the device. Much of the solar radiation reaching the earth surface is composed of photons with energies greater than the silicon band gap. These higher energy photons will be absorbed by the solar cell, but the difference in energy between these photons and the silicon band gap is converted into heat via lattice vibrations called phonons rather than into useful electrical energy which can damage the cell. Different types of the SCs are:

- Crystalline silicon solar cells
- Thin-film solar cells
- Plasmonic solar cells

**SURFACE PLASMONS**

A noble metal nanoparticles exhibit a strong optical extinction (absorption + scattering)
cross-section due to the collective oscillation of free electrons called LSPR. The resonance wavelengths are reported to be sensitive to the size, shape and surrounding medium of the nanoparticle. For the light to be trapped the absorption is not important, but the scattering of the light by metal nanoparticles is important, to utilize the light energy for highly efficient SCs.

**Plasmonics: Scattering and Absorption by Metal Nanoparticles**

The basic principle for the functioning of plasmonic SCs includes scattering and absorption of light due to the deposition of metal nanoparticles. A thin silicon sheet does not absorb light very well. For this reason, more light needs to be scattered across the surface in order to increase the absorption of Si to convert it into the useful electrical energy. It has been found that metal nanoparticles help to scatter the incoming light across the surface of the Si substrate at resonance wavelengths. The equations that govern the scattering and absorption of light for particles, which have dimensions less than the wavelength of light can be written as:

\[
\sigma_{sc} = \frac{k^4}{6\pi} |k|^2 \quad \& \quad \sigma_{abs} = k \text{Im}(\alpha)
\]  

The polarizability \( \alpha \) of the particle is given by:

\[
\alpha = \frac{4\pi}{3} a b^3 \left( \frac{\varepsilon_p(\omega) - \varepsilon_m}{\varepsilon_m + L_x [\varepsilon_p(\omega) - \varepsilon_m]} \right)
\]  

\( \varepsilon_p \) is the dielectric function of the metal particle, \( \varepsilon_m \) is the dielectric function of the embedding medium and \( L_x \) is the depolarization factor, which is the function of the particle shape. For spherical particles, when the polarizability of the particle becomes maximum resonance occurs. The dielectric function for metal with low absorption can be defined as:

\[
\varepsilon_p = 1 - \frac{\omega_p^2}{\omega^2 + i\gamma\omega}
\]

\( \omega_p \) is the bulk plasmon frequency and defined as:

\[
\omega_p^2 = \frac{N e^2}{m \varepsilon_0}
\]

\( N \) is the free electrons density, \( e \) is the electronic charge and \( m \) is the effective mass of an electron. \( \varepsilon_0 \) is the dielectric constant of free space. Many of the plasmonic solar cells use nanospheres to enhance the scattering of light in such a case LSPR frequency in free space can be given as:

\[
\omega_{LSPR} = \sqrt{3} \omega_p
\]

LSPR frequency for spherical particles primarily depends on the free electron density in the particle. The order of densities of electrons for different metals shows the type of light, which corresponds to the resonance.

- **Aluminum** - Ultra-violet
- **Silver** - Ultra-violet
- **Gold** - Visible
- **Copper** - Visible

If the dielectric constant for the embedding medium is varied, the resonant frequency can be shifted. Higher indexes of refraction will lead to a longer wavelength and broaden the resonance range. Gold is highly stable and shows the resonance peak broader than silver. Though silver is cheap in comparison to gold, it is highly unstable and gets oxidized, which affects the resonance frequency. On the other hand, copper is cheaper than silver,
and more absorbent than gold. Aluminium shows the resonance frequency in the UV range and also shows oxidization effect. Plasmonic SCs are considered the future of the industry in comparison with any type of solar cells due to their high efficiency at the approximate cost of second generation of solar cells.

**Plasmonic Solar Cells**

Plasmonic Solar Cells (PSCs) have great potential to drive down the cost of solar power. To make SC a viable energy source, trapping of light is crucial for thin film SCs. So, plasmonic nanoparticles would be used to increase the efficiency of thin film SCs. The scattered light from plasmonic nanoparticles excited at LSPR make them efficient. The design of a PSC varies depending on the method being used to trap light through the material. A common design is to deposit metal nanoparticles on the top surface of the thin film SC. When light hits these metal nanoparticles at their surface plasmon resonance, it is scattered in many different directions. This allows light to travel along the SC and bounce between the substrate and the nanoparticles enabling the SC to absorb more light.

**Recent Advances in PSCs**

There has been some pioneering work in the field of PSCs. One of the main focuses has been on improving the thin film SCs through the use of metal nanoparticles distributed on the surface. The increased scattering provides more photon availability, which causes electron excitation and hence, generates current.

**Catchpole and Polman:** In thin film SCs, path length enhancements up to a factor of 30 were found for optimized shapes as particle shape is a crucial parameter determining the light trapping efficiency.

**Westphalen:** Enhancement for silver clusters incorporated into indium tin oxide and zinc phthalocyanine solar cells.

**Derkacs:** Gold nanoparticles on thin-film silicon gaining 8.3 per cent of conversion efficiency.

**Stenzel:** Enhancements in photocurrent by a factor of 2.7 for indium tin oxide-copper phthalocyanine structures.

**Stuart and Hall:** Achieved enhancement in the photocurrent by a factor of 18 for a 165 nm thick silicon on insulator photo-detector at a wavelength of 800nm using silver nanoparticles on the surface of device.

**Schaadt:** Enhancements up to 80 per cent at wavelengths around 500nm was obtained.
by deposited gold nanoparticles on highly doped wafer-based solar cells.

Pillai: Photocurrent increase of 33 per cent and 19 per cent was obtained on 1.25μm thick silicon on insulator solar cells and planar wafer based cells via deposited silver particles.

Singh and Verma: Theoretical calculations show that Cu nanoparticles can be more useful than Al, Au and Ag nanoparticles to make plasmonic thin film Si solar cells.

APPLICATIONS OF PSCs
The applications for PSCs are endless. The need for cheaper and more efficient SCs is very high. In order to be considered cost effective, SCs need to provide energy for a smaller price than that of traditional power sources such as coal, gasoline or nuclear. The movement toward a greener world has helped to spark research in the area of PSCs. With new technologies (third generation), efficiencies of up to 40-60 per cent can be expected in comparison to first generation SCs whose efficiencies are 30-40 per cent. With a reduction of materials through the use of thin film technology (second generation), prices can be driven down. Certain applications for PSCs are given below:

Space Exploration Vehicles: the main contribution for this would be the reduced weight of the SCs. An external fuel source would also not be needed if enough power could be generated from the PCs. This would drastically help to reduce the weight also.

Rural Electrification: An estimated two million villages near the equator, with approximately 80 per cent of the world population, have limited access to electricity. When the cost of extending power grids, running rural electricity and using diesel generators is compared with the cost of solar cells, many times the solar cells win hands down. If the efficiency and cost of the current solar cell technology is decreased even further then many rural communities and villages around the world could obtain electricity. Specific applications for rural communities would be water pumping systems, residential electric supply and street lights.

Power Stations: If SCs could be produced on a large scale and be cost effective, then entire power stations could be built in order to provide power to the electrical grids. With a reduction in size, they could be implemented on both commercial and residential buildings with a much smaller footprint. The SCs could help to power high consumption devices such as automobiles in order to reduce the amount of fossil fuels used and to help improve environmental conditions.

Low Power Electronics: Essentially, SCs could be used to replace batteries for low power electronics. This would save everyone a lot of money and it would also help to reduce the amount of waste going into landfills. SCs could also provide power to lighthouses, or even battleships out in the ocean. It can also be applied to other electronic devices to make them self-power driven when the sun is out. There are solar cell phone chargers, solar bikes, solar cars that people can adopt for daily use.

CONCLUSION
Research in PSCs is rapidly exploiting the benefits offered by plasmonics in tandem with those of thin film technology. The advantages of using plasmonic particles is to use them on any thin film SC (silicon or organic). The metal nanoparticles of different size, shape and embedding medium can enhance the efficiency of the solar cells over a large range of the electromagnetic spectrum. Hence, PSCs are promising candidates to drive down the cost of solar energy generation with high efficiency.

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