The need for solar energy
For the last few decades, the use of all fossil fuels has risen constantly throughout the world, and there are no indications that this trend will reverse in the foreseeable future. It is a well known fact that supplies of fossil fuels are (economically) limited, and eventually we must replace their use by sustainable technologies completely. Advanced technologies take time to mature technologically, and they take even more time to be economically feasible. Considering the enormous amount of fossil fuels consumed every year this means the scale on which sustainable resources must be deployed eventually will be unprecedented by today’s standards, and we must allocate significant scientific resources now to solve this problem before we are too late. Solar energy promises to be one of the main driving forces behind this sustainable revolution. Taken the expected mass deployment combined with the economies of scale, there can be a benefit in the increase of efficiency of solar cell of even a few percent. While the currently best performing solar cells have an efficiency of over 40%, these cells are very expensive to fabricate, and there is considerable research into thin film solar cells, which promise to be a large scale cheap solar technology.

Thin film solar cells
The last few years there has been a strong research focus on thin film cells, and with good reason. They use less material to produce, they are flexible and have a high collection efficiency. A solar cell can be seen as a light sensitive PID-diode with terminals on both ends. In the PIN region of the solar cell, from here on called the photo-active layer, light is absorbed at a certain statistical rate. If a photon is absorbed its energy - determined by its frequency - is used to bring an electron from a lower energy band where it is attached to its atom to a free conduction band. These bands are separated by a certain energy level, and an electron is not allowed to be in between these two bands. If the photon is absorbed we have two oppositely charged particles, the electron and the charged atom, and we need to ‘harvest’ them to build up a voltage potential over the solar cell. In thin film solar cells movement of free charges in the photo-active layer is mainly determined by the drift, which depends on the applied electric field and mobility of the medium.

In thick solar cells, the primary force of movement is diffusion, where free charges follow a random Brownian motion path and
are collected ‘by accident’. This would not be a problem if all free charges would surely be collected, but unfortunately the longer the path before a free charge is collected, the bigger the chance that it recombines with a particle of opposite charge, thereby emitting a photon.

Here we see an interesting trade-off appearing when we combine thin film cells with conventional solar cells. A thicker solar cell will make it more likely that a photon is absorbed, which is particularly true for lower frequencies, while at the same time the collection efficiency drops with increased thickness due to the prevalence of the diffusion over drift as the dominant separation process. Thus, we need a solution to optimize the absorption of light in a thin structure.

**Optimizing photon collection**

There are essentially two ways to optimize the absorption. The conventional method is minimizing the reflection by a coating, so that all incident light at the surface is transferred to the photo-active layer. Depending on the desired bandwidth of this coating, these coatings can be fairly complex. A second technique is the trapping of the light in the solar cell structure. By twiddling with the geometry of the cell at a nanoscale a broad range of interesting effects can be obtained that will trap the light in a structure. These techniques have become feasible only recently with the ongoing advancements in nano-technology and the corresponding benefits in production scale.

A technique that is gaining rapid popularity with the advancements in nano-technology is the use of surface plasmonic polaritons. These are electromagnetic waves that are trapped or guided along certain configurations. All materials have three properties on which the propagation of electromagnetic waves depend, permittivity, permeability and conductivity. While relative permeability is usually close to zero, relative permittivity can vary over a broader range. A particular interesting effect is that the apparent permittivity of many materials varies with frequency. This effect is called dispersion. It turns out, that for some frequency band in and around the optical range the permittivity of a material is negative, and the interface between a positive and a negative permittivity a surface plasmonic polariton can exist. Note that this effect is not the same as meta-materials, which we are hearing quite a lot from lately, where we need both the permittivity and the permeability to be negative. A negative permeability is created typically by tuning some specific structure to obtain an effective negative permeability. Surface plasmonic polaritons are typically seen at the interface of a metal, such as silver or gold, and a dielectric such as a semiconductor. Electrons start oscillating at this interface, called surface plasmonic resonance, and as a result we have a sort of ‘trap’ around this interface. The optimum for this oscillation is when the two materials at the interface match each others permittivity in the opposite sign. This perfect match, unfortunately, usually only happens at a specific frequency, and around this frequency, \[\text{Figure 1: How thin-film solar cells work (source: www.howstuffworks.com)}\]
where we still have opposing signs in the permittivity of both materials, we will see a less than optimal oscillation due to scattering of incident wave.

Why is all this important? We assume that all electron-hole pairs are actually absorbed by their corresponding collectors, which is a reasonable assumption since our structure is very thin. Unfortunately, most light is reflected at the various layers of the solar cell structure, and a typical 'plain' thin film solar cell will have an efficiency of only a few per cent. Most of the light will be scattered by the lowest layer, the reflector. This reflector is typically made of a highly conductive material, such as aluminium or silver. This high reflectance will guaranty us that the light will pass through the photo-active layer twice. What we want is to use the surface plasmonic resonance technique in such a way, that the electromagnetic wave adheres to it. While a back-reflector will take care of this for some part, its contact surface is relatively small. To increase the surface, we can corrugate it, either in a structured, thus tuned, or randomized way, or we embed extra metallic particles inside the photoactive layer to enhance the contact surface. This approach, however sounding promising initially, comes with a number of physical drawbacks. First, by adding particles to the photoactive layer, we decrease the volume, and to compensate we need to increase the layer thickness, thereby reducing internal quantum efficiency. Secondly, the surface plasmons exists on both sides of the medium interface, and while on the photo-active side the energy is dissipated into electron-hole pairs, on the metallic side this energy is converted into heat. Third, the inclusions will, when the permittivity is not perfectly matched, also act as scatters, blocking part of the incident light to reach the back reflector. However, light that does reach the reflector and scatters from this reflector will be partly trapped between the back reflector and the metallic inclusions.

Problem analysis

So, do the drawbacks weight in against the benefits? This question really hard to answer without experiments, and while you would certainly be able to create a whole lot of different samples in a laboratory, this is very costly. Thus we resort to numerical modelling of the problem. Using a computational approach, it is easy to test dozen of different structures with relatively small effort. The method we use is the finite difference time domain method (FDTD). In this method we discretise time and space, and simulate the time behaviour of any given structure. The creation of an appropriate simulation scenario is something of an art, since a structure is typically much bigger than what fits in a computer memory of a powerful workstation PC, especially in 3D, and we have to come up with various tricks and approximations to make a useful simulation. Without going into details - you can find them in my M.Sc. thesis - we have run many different scenarios for a wide frequency band to see which additions performed best. All inclusions materials have been silver, since it has excellent electric properties for a reasonable material price. What we have seen from various simulations, is that the benefits that this technology promises, we have seen only moderate increases in efficiency, with the highest efficiency peaking at 5%. While the absolute increase against the plain flat cell at 3% is certainly impressive, it is far from efficiency of over 40% seen in the best multi-junction solar cells, and it is questionable if the increase in manufacturing price - after all, we are talking nanotechnology here - can justify this increase.

What we did find, however, is that by aggressively corrugating the interfaces between the layers, efficiency ratios of nearly 30% were attained. This is a highly surprising results not the least to say, and these results are - as opposed to particle insertion in the photo-active layer - are not yet backed by lab experiments as far as I know. Possibly this is due to wrong approximations in our numerical model, or this could be a large breakthrough in the thin film solar research.

So is plasmonic resonance the next big thing in solar energy? I have my personal doubts, and what I heard from around the university, other scientists share these doubts. Numerous results are still being published from around the world - including from leading research institutes - and it would be too soon to dispose this technique. Much more additional research must be carried out before this topic is definately settled, and I think this is a great opportunity for students to explore as graduation project, as I have done.