Bridge between research in modern physics
and entrepreneurship in nanotechnology

Quantum Physics

*The physics of the very small
with great applications*

Part 2

QUANTUM PROPERTIES & TECHNOLOGY

Learning Station VI:

From photoelectric effect to digital imaging

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Lifelong
Learning
Programme

Introduction to part 2: Quantum properties and technology.

In part 2 of the learning stations we explore the bridge between quantum physics and its technological applications. We will use the knowledge acquired with the first five learning stations to understand further quantum properties of materials that can be applied in many technological advances.

Also in this part 2 we find back both classical and quantum concepts showing the path from classical to quantum physics and the accompanying modern technological advances. We propose at the end of each chapter a summary of the main classical and quantum concepts in the form of an exercise, as done for part 1.

Here below you find an overview of the content of each learning station of part 2. This is meant to clarify the learning line and to keep an eye on the targets and the point from where we started.

Learning station VI: From photoelectric effect to digital imaging

Starting with the working of a digital camera we will discover that digital imaging is possible thank to a quantum effect called the photoelectric effect. We will study this phenomenon, first trying to explain it using classical physics and then using the acquired knowledge about quantum physics. We will also analyse some technological applications the functioning of which is based on the use of photoelectric effect.

Learning station VII: Semiconductors.

In this learning station we start from the energy levels of electrons in an atom and investigate what happens to them when many atoms are put together. We will discover that the characteristics of elements in the periodic table are also a consequence of quantum properties as well as electric conduction. We will then see what are the many technological applications arisen thanks to the understanding of these properties of materials.

Learning station VIII: Tunneling & STM

Learning station VIII introduces still another quantum effect: tunneling. We will see that microscopic objects and light can pass through an energy barrier, though they do not have enough energy to overcome it, thanks to their wave-particle nature. We will also discover that tunneling has many interesting and useful applications, such as flash memories and Scanning Tunneling Microscopy (STM).

Learning station IX: Spin and its applications

There are many undefined properties of matter, like mass, that objects simply seem to have. We do not really know what mass is, but we do know how this property of matter manifests itself. This helps us to introduce a quantum property of matter: spin. Spin has no counterpart in classical physics. However we can study how objects with spin behave, in order to understand and use it for technological applications, like Magnetic Resonance Imaging (MRI) and spintronics.

Learning station X: Atomic Force Microscopy

This learning station makes use of the concepts introduced in learning station VIII and it presents still another application of tunneling: the Atomic Force Microscopy (AFM).

Learning stations XI: From quantum mechanics to nanoparticles and their applications

This learning station bring us first of all to the world of nanoparticles and their properties. Nanoparticles are quantum mechanical systems consisting of many atoms or molecules: their features differ from those of the simple quantum mechanical systems so far studied. Many of these features can be used for nanotechnological applications and are currently the subject of intense scientific research.

Learning stations XII: Microbial Fuel Cell

The subjects studied in learning station XII bring us into the relationship between quantum mechanics and disciplines like biology and chemistry. We will go into this topic by analysing the functioning principle of microbial fuel cells.

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Part 2: Quantum Properties & Technology

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Learning station VI : From photoelectric effect to digital imaging

1 What does your digital camera actually do?

Figure 1 and 2: a digital camera with 24X optical zoom and 14 megapixels (source: KHLim)

Have you ever asked yourself what actually happens when you take a picture with a digital camera and you see your picture appearing on a digital screen?

Maybe not, since you are probably too young to have experienced film photography, and for you it's obvious that your picture will appear on a screen.

In fact, this is far from obvious. Something at the very fundamental physical level happens there, hidden in the internal structure of your camera. Let's reveal the mystery.

When you take a picture, with any camera, or with your own eyes, through the lens you collect ……………………

This …………………… , originally coming from a source, like the sun or a lamp, has interacted with the matter present around the camera. As a result, when it arrives at the lens, it encodes some information concerning the relative positions and shapes of objects and their colour in the region around the camera.

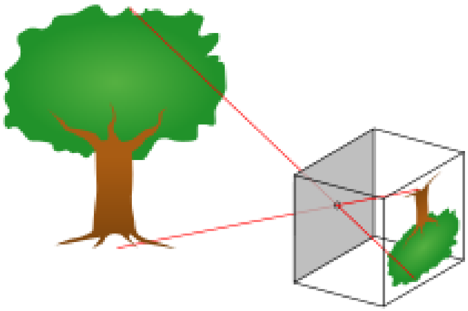


Figure 3: Light arriving at the back side of the 'camera obscura' must contain information on the tree. Otherwise, how could a scaled image of the tree ever appear there as a result of the incident light? (figure source: wikipedia)

It's the same with your eye: you collect …………….. through the ………………… in your eye, and by analyzing it you are able to extract …………………………. about the matter present around you.

This information about matter around us encoded in light is what we want to detect, transform and store with a camera, so that we can use it afterwards.

Where does the difference lie between an old film camera and a digital camera according to you? (more options are possible)

(a) At the level of the collection of light (lens optics)

(b) At the level of the transformation of the information encoded in light.

(c) At the level of the storage of the information encoded in light.

In an old film camera, the information is transformed into a pattern on a photographic film (or plate). It's a chemical process, induced by the light coming on the film, which changes the features of the film permanently. Therefore, the photographic film or plate also works as storage.

But in a digital camera, into what is the information originally encoded in the collected light transformed?

To answer this question, it might help to think of the moment you connect your camera to the computer and visualize the pictures on the computer external screen.

What do you use to connect camera and computer?

…………………………………

What happens there in? (in other words: how is the information physically transferred?)

…………………………………………………

Something moves at a more microscopic level : what?

………………………………………

Figure 4: connecting your camera to the computer (source: KHLim)

As you have seen in the previous learning stations, light, as much as matter, can behave either as a ……………………… or as beam of …………………………… .

The particles of which light is made are called ……………………… .

A very nice example of how these two ways of being coexist in light is the double slit experiment executed photon by photon (see learning station IV Wave Particle Duality).

There you clearly see that what is actually detected are the …………… which one by one leave a spot on the screen. All together they form a pattern, in that case the diffraction pattern typical of ………… behaviour.

In fact, we can say the same for a camera. What the camera detects are the …………………… going through the camera lens.

Then the digital camera in some way converts the information about the world encoded in the photons into an electrical signal, that is an electric ………………… made of moving ……………… .

There is still one step between the electrical signal and the files where the information is stored. As you probably know very well, everything that can be understood by a computer must be expressed as a series of the digits …… . and ……. This is the meaning of 'digital'.

A digital camera must then convert the electrical signal in a digital signal that can be read and stored by the computer.

In this learning station we focus on the first part, the conversion from a photon 'signal' to electrical signal.

To summarize:

A camera, film or digital, through the lens collects ………………… which can be described as beams of particles named ……………

The collected ………………… altogether encode information about the world in the region around the camera.

A digital camera first transforms the photon-based coding of the information into an electrical signal, that is a coding based on a current of moving ……………………

This electronic signal is afterwards converted in a digital signal (made of ……………… and ……………… which can be understood by the computer and stored in a file.

But how can we convert the photons collected by the camera lens into a current of moving electrons?

2 Photoelectric effect

Albert Einstein received the Nobel Prize in Physics in 1921.

For which theory do you know Einstein?

………………………………………………………………

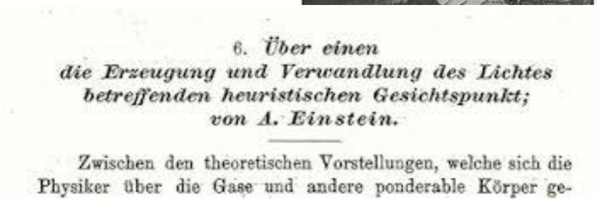
Check on the internet. For which theory did Einstein receive the Nobel Prize?

…………………………………………………………………………………

We all associate Einstein with its elegant theory of relativity.

But his contribution to physics in the 20th century is broader than that.

Einstein is actually also one of the fathers of quantum mechanics, and, as you will see in the next sections, you should thank him every time you use your digital camera.



6. *Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt;*
von A. Einstein.

Zwischen den theoretischen Vorstellungen, welche sich die Physiker über die Gase und andere ponderable Körper ge-

Figure 5: Einstein at the desk of the patent office in 1905, his wonder year. (Photo source: Wikipedia)

The physical phenomenon making it possible to transform the information encoded in the detected photons into an electrical signal, within your digital camera, is called the **photoelectric effect**.Surprisingly enough, this is also one of the first inexplicable phenomena that, in the beginning of the 20th century, brought classical physicsa into a deep crisis and led to the development of quantum mechanics.

Qualitatively, the photoelectric effect is simply the fact that **electrons can escape from the surface of a metal when light shines on it**.

In general, electrons can only escape from the surface of a metal when energy is given to them. The minimal energy needed by an electron to free itself from the surface of the metal is different for different metals. For example for zinc we will call it E_{zinc} .

The **qualitative** features of photoelectric effect can be perfectly explained by classical physics. Light modelled as an electromagnetic wave brings an electric field on the electrons in the metal, which are ………………………………………… particles.

The electric field exerts a force on a charged particle, and a charged particle in an electric field acquires energy. When the field is strong enough, electrons can therefore get enough energy to escape from the metal.

But **quantitatively**, one is directly confronted with the very strange features of the photoelectric effect.

Whether electrons can escape or not, happens to depend on the colour (frequency) of the light we shine on the metal. There is a **minimal frequency** for which the electrons can escape.

2.a Photoelectric effect in the classroom

You can demonstrate the photoelectric effect with a simple experiment in the class.

You need an electroscope, a zinc plate, a glass rod and a piece of paper to charge it (all material normally available in the school lab). You need also a UV-C lamp, which is normally not available in the school lab but can be bought in the water gardening section of a do-it-yourself store[1].

Fix the zinc plate on the electroscope and charge it negatively by using the glass rod rubbed with the piece of paper.

You can now let different kinds of light shine on it.

You will see that the electroscope remains charged if normal white light shines on it. You can also try with an infrared lamp. Nothing happens with that either. The electroscope remains charged.

But when you let the UV-C ‘light’ shine on the charged electroscope, you will see that the electroscope quickly loses its negative charge.

---

[1] UV-C light is used in water filters to kill bacteria. It is rather energetic electromagnetic radiation, so you should be very careful with it. Let it shine on the zinc plate and not on your skin or in your eyes! Cover it with a dark paper roll so that the light only shines in the direction of the zinc plate.

This means that the carriers of negative charge in the metallic plate, that is …………………………… have managed to get out of it when the UV-C 'light' was present.

As you know, UV radiation has a …………………………… frequency than visible light and infrared radiation. You need a lamp emitting radiation with ……………………… high enough to free electrons from the zinc plate.

The experiment does not work if you charge the zinc plate positively. Why?

………………………………………………………………………………………

………………………………………………………………………………………

Figure 6: Belgian teacher Hans demonstrates the photoelectric effect with an electroscope and a UV-C lamp.

Classical physics cannot explain what you have just seen with the electroscope.

Why should electrons only escape from the metal with incident light of a certain frequency?

As you have seen in learning station 3, the classical model of light depicts it as an electromagnetic ………………

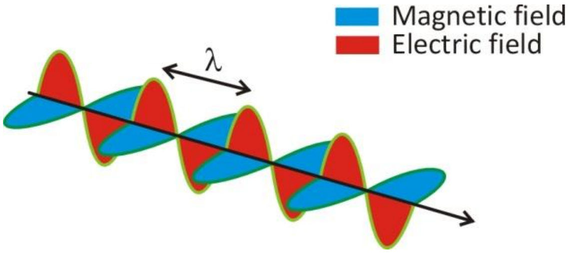


Figure 7: An electromagnetic wave is made of an oscillating electric field and, an oscillating magnetic field perpendicular to it, with the same periodicity. (Source: photonicswiki)

If the magnitude of the electric field is large enough, the electrons should be able to get enough energy to escape, independently of the time periodicity with which the electric field oscillates.

2.b Photoelectric effect: a virtual experiment

By using a virtual experimental setting, you can better understand the mysterious quantitative features of the photoelectric effect.

Open the PhET applet: https://phet.colorado.edu/en/simulation/photoelectric

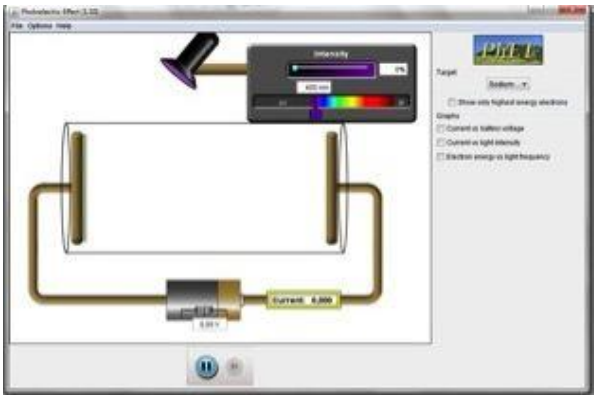


Figure 8: a screen print of the PhET 'photoelectric effect'.

The virtual experimental setting

First look at the setting without changing any parameters. You see that light, or more generally electromagnetic radiation, can shine on the metallic plate on the left, and that another metallic plate has been placed in front of it, on the right.

The two plates are enclosed in a vacuum tube and are externally connected by a conducting wire. We can measure the current in the wire.

Choose now the value of the potential difference between the two plates as 3,00 V.

In the right column you can also choose the metal for the left plate on which light will shine.

To reproduce the situation of the experiment with the electroscope you have seen in the class, you have to choose ……………………………

We will not change the potential difference and the kind of metal anymore during this experiment.

Interplay between wavelength/frequency and intensity of the incident radiation

Switch the light on now, by choosing the intensity above as 50% of its maximal value. Don't change the light wavelength for the moment.

Does the photoelectric occur in this situation? Yes/No

Now slowly increase the intensity to the maximal value.

Does the photoelectric start to occur for this frequency and a higher intensity of light? Yes/No

Now let the intensity stay at its maximal value and slowly vary the wavelength to the infrared (IR) – this means a longer/shorter *(longer)* wavelength corresponding to a higher/lower frequency.

Does the photoelectric occur for the maximal intensity and ……………………. frequencies? Yes/No

Now let the intensity stay at the maximal value and slowly vary the wavelength to the ultraviolet (UV) – this means a longer/shorter *(shorter)* wavelength corresponding to a higher/lower frequency

Does the photoelectric occur for the maximal intensity and ……………………. frequencies? Yes/No

Find the wavelength for which the photoelectric starts to occur for zinc:

λ = ……………………………

Check the measured current below. Can we measure an effect with this wavelength?

Yes/No

Find the wavelength for which we can measure a photoelectric current for zinc in this experimental setting:

λ = ……………………………

Finally, for this value of the wavelength gradually lower the intensity of the incident radiation. What happens to the current?

……

Choose now the minimal wavelength possible with this experiment, λ = 100 nm.

What happens to the current when you change the intensity?

Higher intensity corresponds to a higher/lower current.

Let us summarize the **quantitative features of the photoelectric effect** we have observed:

1. There is a minimal ……………… of the incident light for which …………… can escape from the metallic plate.

2. Increasing the ………………………… of the incident light for a given frequency, does not affect whether electrons can escape or not for this frequency.

3. For a given frequency for which the photoelectric effect does take place, increasing the intensity of the incident light leads to an increase of the produced ………………………

Relation to the experiment you have done in the classroom

Look up on the internet which is the range in wavelength for UV-A, UV-B and UV-C 'light':

UV-A: between …………………… nm and ………………………………… nm

UV-B: between …………………… nm and ………………………………… nm

UV-C: between …………………… nm and ………………………………… nm

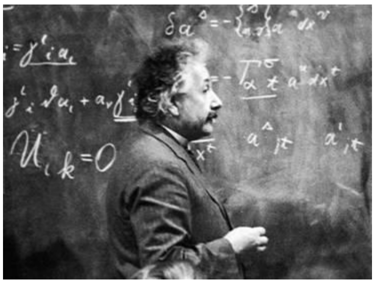
According to this information and what you have determined by using the applet, you can conclude that, to observe photoelectric effect for zinc, you need a lamp producing electromagnetic radiation in the ………………… range.

The experiment with the electroscope does not work with the standard UV-A or B lamp of the school lab and also not with a white or infrared lamp. One needs to buy a pond-filter lamp emitting radiation with a shorter/longer wavelength and a higher/lower frequency with respect to the standard school lab UV lamp.

By using the applet we have been able to observe the quantitative features of the photoelectric effect in more detail. But this does not mean that we can explain them!

To achieve this, we will need to consult Einstein for help first!

3 Einstein's theory of photoelectric effect



The hypothesis of Einstein to explain the photoelectric effect is that energy can only be exchanged between the incident light and the metal plate in **discrete packets of energy** (quanta)

$$E = h\ f$$

where f is the frequency of the incident light and h the Planck constant.

One electron can only take one energy packet. These packets give the energy of the particles we now call photons.

Now you can explain, by using the hypothesis of Einstein, the three mysterious quantitative features of the photoelectric effect you have observed with the real and virtual experiments.

1. **There is a minimal …………………………………… of the incident light for which ……………………………………can escape from the metallic plate**

   An electron needs to get at least the energy E_{zinc} to get out the metal.

   One electron gets one energy packet of energy E = h f from light.

   Thus the electron can escape when h f ……… E_{zinc}. *(Fill in ≤, ≥, <, > or =)*

   And by isolating the symbol f at one hand of the equation and the others at the other side, you'll find:

   f …………………………

   The minimal frequency f_0 the incident light for which the photoelectric effect can occur in the metal is

   f_0 = ……………………………………

2. **Increasing the …………………………………… of the incident light for a given frequency, does not affect whether electrons can escape or not for this frequency.**

   When the intensity of the incident light increases, more ……………of energy become available, but the ……………… of a single packet is not affected.

   Since one electron can only take one ……………, the intensity does not play any role in the reasoning above concerning the minimal frequency.

3. **For a given frequency for which the photoelectric effect does takes place, increasing the intensity of the incident light leads to an increase of the produced …………………………………….**

   Higher intensity means that there are …………………… packets of energy available. As a consequence there will be more ……………… in the metal which will be able to escape. This results in a higher ……………….

An electron needs energy to escape from the surface of a metal. One can illustrate this by drawing the electron in an energy well. The depth of the potential well gives the energy needed by the electron to escape. From the incoming electromagnetic radiation the electron gets one packet of energy. The electron can escape when this energy is greater or equal to the depth of the well. The difference between the energy of the packet and the depth of the well, is the kinetic energy with which the electron comes out.

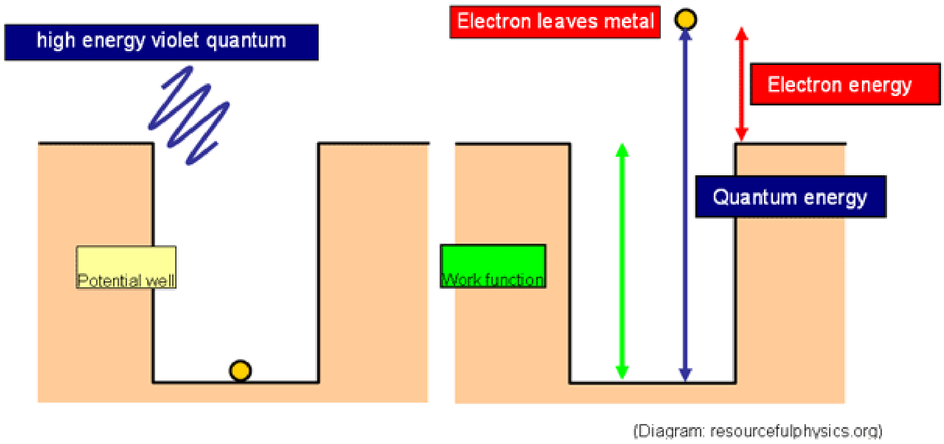


Figure 9: the photoelectric effect schematically represented by using the concept of an energy well (source: Institute of Physics, http://tap.iop.org/atoms/quantum/502/page_47014.html , originally from resourcefulphysics.org). In the figure: Electron energy is the kinetic energy of the escaped electron and Quantum energy is the energy of the UV quantum which is absorbed by the electron.

4 Inner photoelectric effect and charge-coupled device

If you think back at the experiment with the electroscope and the zinc plate, you can remember that no effect was seen with visible light: you needed a high frequency UV-C light to see the photoelectric effect.

But this is of course not good if we want to convert the visible light captured by the camera lens into electrons! We need a similar effect which however works with electromagnetic radiation in the **full visible spectrum**.

Good news is that a **semiconductor** like **silicon** does display some kind of photoelectric properties with visible light! However, while in the standard photoelectric effect an electron in a metal can escape *from the surface of the metal* by acquiring the energy of the photon, in the case of a semiconductor the photon allows a bound electron (in the semiconductor valence band) to 'jump' to the conduction band and thus to move freely *inside the semiconductor*. For this reason the term **inner photoelectric effect** is used: the 'freed' electrons remain inside the metal.

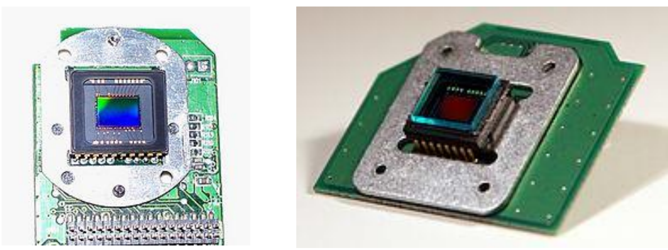


Figure 10 : CCDs from two different 2,1 pixel digital cameras (source: wikipedia)

A **charge-coupled device (CCD)** is a chip that converts electromagnetic radiation (photons) into an electric signal (electrons). In your digital camera you will find it behind the lens.

Normally it uses a thin silicon wafer. This is divided in millions of squares, or **photosites**, corresponding to the **pixels** in the final image. For instance, a '1000 by 1000' square has 1000000 photosites, which results in 1000000 pixels, or 1 megapixel.

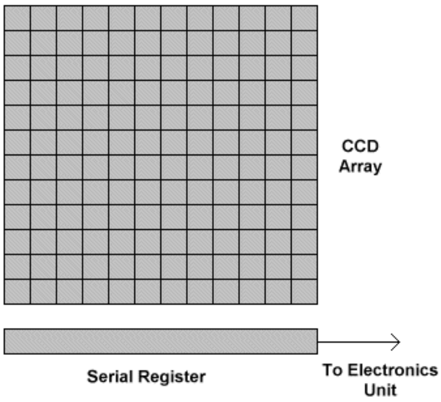
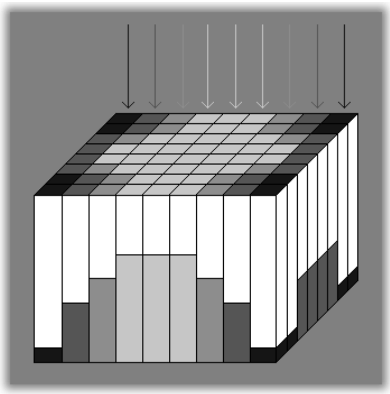


Figure 11: a 12x12 photosite CCD

(Source: Starizona http://starizona.com/acb/ccd/introimaginghow.aspx)



When a photon hits a square, an electron is released. The electrons are stored within the walls of a photosites.

The photosites producing more electrons, resulting in a higher current, are associated with lighter pixels in the final image, and photosites producing a lower number of electrons with dark pixels.

Figure 12 : reconstructing a black and white image by counting the electrons that have been produced by photoelectric effect on each photosite (histogram under the silicon square). The photosites where less electrons has been produced are darker, where more electrons have been produced are lighter

(Source: Starizona http://starizona.com/acb/ccd/introimaginghow.aspx)

But in this way we can only reconstruct a **black and white** image.

How can we reconstruct a **colour image** with the same principle?

What can you use to select light of a certain colour in an optics experiment?

………………………………….

The simplest way to reconstruct a colour image, used in most digital cameras, is to put a filtering mask on the CCD, as shown in the figure below. In this way each small square will only receive the photons of the chosen colour. So, ………………… of the old photosites become one colour photosite. One can detect how many blue, red and green photons have arrived there. Since with the colours ………………… , ………………… and ……………… you can make all colours, you can reconstruct a full colour picture in this way.

The inner photoelectric effect in semiconductors is also used in **photodiodes**. A **solar panel** is a large surface photodiode (see learning station VII Semiconductors).

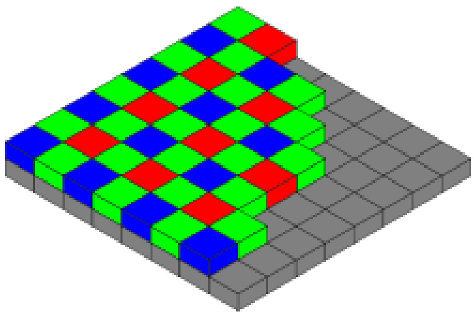


Figure 13: the colour-filtering mask on a CCD (source: wikipedia)

5 Concepts in Learning Station VI

Complete by adding the missing concepts

Classical concepts

Qualitatively photoelectric effect can be explained by classical physics: light, modelled as an ………………………………………, brings an electric field on the electrons in the metal which acquire energy. The field should be ………… enough in order for the electrons to get the necessary energy to scape.

Quantum concepts

Quantitatively we need quantum physics to explain the photoelectric effect: whether the electons can escape or not depends on the ………………………… of the light shining on the metal. There is a ……………………………… for which the electrons can escape.

Hypothesis of Einstein: energy can only be exchanged between the incident light and the metal plate in .... of energy (quanta): $E = hf$.

Increasing the …………………………… of the incident light for a given frequency does not affect whether the electrons can escape or not.

Increasing the intensity of the incident light for a given frequency, for which the photoelectric effect does take place, does increase the ………………………………………