OKI DATA Tech Tech Journal
Grow the future

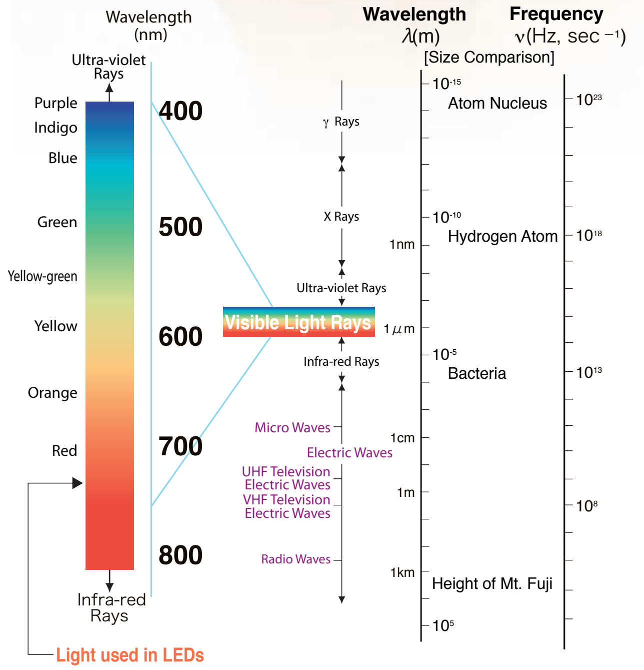
④How Do LEDs Emit Light?

Introduction

In this issue we will cover how LEDs emit light.
The process of light emission is generally supported by the theories of quantum mechanics and solid state physics. These theories, which successive Nobel physics prizewinners and numerous eminent physicists laboured to formulate, explain the 'atom', in a world far removed from the experience of our everyday lives. Please note that some details in this account have been simplified.

What is light?

Before going into how LEDs (light emitting diodes) emit light, let's first take a brief look at light itself. Since ancient times, man has obtained 'light' from the sun's rays, as well as from heat generated by candles and lamps. This heat energy is converted into light energy to become a light source. (The word 'energy' comes from the Greek energeia; en +ergon meaning 'in' and 'work', and literally means 'power to do work stored within an object', or more simply, '**potential energy**'.)
In 1879 the incandescent light bulb was invented by Thomas Edison. In the light bulb, an electrical current is passed through a filament inside the bulb, which then heats up and emits light. This light is the result of electrical energy converting into heat energy which in turn changes into light energy. The concept of electrical energy converting into light energy is an important one; although these energies can convert from one type to another, they cannot disappear or create themselves from nothing.



[1m= 1000mm, 1mm =1000mm, 1mm =1000nm]
Wavelength (λ) x frequency (ν) =light velocity (χ)

Figure 1
The relationship between light and other electromagnetic waves

But what exactly is light? **It is a type of electromagnetic wave**, similar to those used in televisions and radios. In 1861 the Scottish physicist J.C. Maxwell came up with the theory of interrelated electrical and magnetic (electromagnetic) waves which are propagated through air. As the rate of propagation is exactly the same as the speed of light, he suggested that light is an electromagnetic wave. The existence of electromagnetic waves was confirmed in experiments conducted by the German physicist Heinrich Hertz in 1888. Hertz measured reflection and refraction and proved that electromagnetic waves and light have the same properties, confirming that light is actually an electromagnetic phenomenon. (Hertz's name is used for the unit of frequency Hz in honour of his outstanding achievement.)
As light is a wave, its wavelength and frequency are fixed. The different colours of light arise from differences in wavelength and frequency. Figure 1 shows the relationship between visible light and electric waves.
It is commonly said that light and electric waves travel 7.5 times around the globe in just one second. Both travel at this speed because they are both electromagnetic.
This means that **light (electromagnetic waves) can be produced directly from electricity**, in the same way as electric waves. In other words, unlike the light bulb in which electrical energy first converts into heat energy, electrical energy can change directly into light.
Light bulb: Electrical energy→ Heat energy→ Light energy
LED: Electrical energy→ Light energy

The benefits of LEDs are numerous; unlike incandescent light bulbs they do not become hot and can be miniaturized as they do not need to be placed in a glass vacuum, which means that the conversion from electricity to light is very efficient (approximately 8 times more efficient than the incandescent light bulb and twice the efficiency of fluorescent lights), and they also have an exceptionally long life.
In the 'Light for the 21st Century Project', one of several projects masterminded by the Japanese government, research into improving the efficiency of LEDs for general lighting use is under way. With its unlimited potential, the LED can surely be hailed as 'the light source of the future'.

Now that we have an understanding of the nature of light, we can look at the process of LED light emission. An LED contains a light-emitting crystal made of gallium (Ga), arsenic (As) and phosphorous (P)[*1] (technically known as a **compound semiconductor**), in which electrical energy is converted directly into light. In order to understand the principle of LED light emission, we should take a glimpse into the remote world of the atom.

An introduction to the world of the atom: Substance ➡ Molecule ➡ Atom

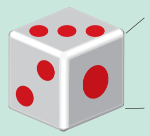
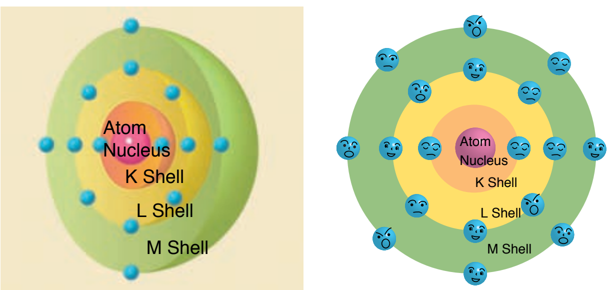


Figure 2 Atom Scale Image

All substances are composed of molecules (for example, water is composed of the molecules H_2O), which in turn consist of a variety of particles with widely differing chemical properties known as 'atoms'. Different types of atoms are generally known as 'elements'. Atoms are approximately 0.00000001cm (10^{-8}, or a hundred millionth of a centimetre) in size; the world of the atom is miniscule. To visualize just how tiny atoms are - there are 100 million of them in only one face of the 1cm dice illustrated in Figure 2 ! Even with the aid of the latest in scanning tunneling microscope technology, it is only possible to view the layout of atoms in this microscopic world. The atom itself has yet to be seen by man; but, thanks to the efforts of many scientists, a model of the atomic structure has been produced that even the layperson can understand. To help picture the structure of an atom, imagine you have been magically shrunk and transported inside one. The atom structure in Figure 3(a) shows a central nucleus surrounded by multiple shells or 'shells' around which electrons revolve.[*2] These shells surround the nucleus, becoming progressively larger the further they are from it. The 3-dimensional representation in Figure 3(a) is rather complex, and a flat image, similar to the one in 3(b), showing electrons orbiting the nucleus in concentric circles, is commonly used. As you know, there are negative and positive (or plus and minus) electrical charges, and the electrons are negatively charged. The nucleus of the atom, on the other hand, is positively charged.[*3] As the nucleus is housed inside the atom, obviously it is smaller than the atom itself, and is thought to be approximately 0.0000000000001cm (10^{-13}cm). The electrons are believed to be approximately the same size as the atom nucleus, although their precise size remains unknown.



(a) Electrons revolving around shells surrounding the atom nucleus

(b) A flat cross-sectional image of the atom showing electrons circling around the atom nucleus in concentric circles

Figure 3 Model of Atom Stucture

Light emission from substances

The gallium (Ga), arsenic (As) and phosphorous (P) crystal used in LEDs is composed of a vast number of atoms and a huge number of electrons. For simplicity, we shall track the activities of an individual electron. While rotating, the electron circulates around each shell, as illustrated in Figure 3. An important point to remember is that when the electron rotates in the shell furthermost from the atom nucleus (shell M in the diagram), **it is not greatly influenced by the nucleus and can easily free itself from the atom's structure**. Weird and wonderful things happen in the world of the atom, as we shall now go on to see.

Producing an energy gap

Let us say that the electron in this outermost shell initially carries an **energy** amount of **1**. The electron is then subjected to an external stimulus, such as **light, heat, or electricity**, which gives it an additional amount of energy, say an amount of **2**. Now the amount of energy carried by the electron is **1+ 2 =3**, and it is in a high energy state **3**. The electron feels unstable carrying so much energy and wishes to return to its original state **1**. It does this by releasing the amount of energy it has just taken on board **2** in the form of light. This is how a substance emits light.

To summarize, **if the electron is exposed to external energy and an energy gap (a different energy state) is produced, light emission can be induced**. We shall go on to look at this in more detail on page 3, but basically, with various technical adjustments, the LED applies this principle of light emission via the energy gap in the gallium (Ga), arsenic (As) and phosphorus (P) crystal. In an actual LED, **the energy used for light emission is provided by batteries or other source of electricity**.

The electron roller coaster

Please refer to Figure 4. A gallium (Ga), arsenic (As) and phosphorus (P) crystal contains many electrons, but here we shall again concentrate on just one to avoid confusion. Within the crystal, as well as the electron's own atom, there are many other atoms tightly packed around it in all directions. The energy held by each electron can vary to some extent because of the influence the electrons have on each other, but in this model, it is indicated by a single, fixed level.

Let's presume the magic wand has been waved and you are now firmly in the world of the atom, seated on board the electron roller coaster in Figure 4. As explained earlier, when the electron receives energy in the form of light, heat, or electricity from an external source, it is forced up into a high energy state.

[*1] Most of the transistors and diodes we call semiconductors[*8] are made of silicon (Si), but LEDs are made of a gallium (Ga), arsenic (As) and phosphorus (P) crystal, and are known as compound semiconductors which are categorized differently to single element semiconductors, such as those made from silicon (Si).

[*2] There are many different ways to explain and illustrate the atom structure, but we have chosen the style in Figure 3 because it is the most simple to understand.

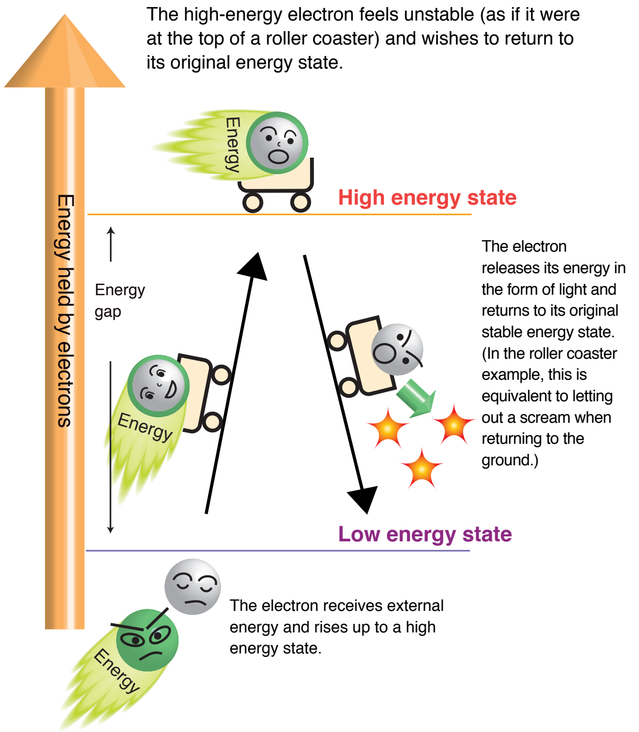


Figure 4
Atom roller coaster and energy held by electrons

The traditional fairground roller coaster is powered by a motor and carriages are lifted up to a precarious height before being dropped at high speed and landing safely on the ground. Inside the roller coaster carriages, we scream as we come hurtling down towards the ground (and then give a sigh of relief!). It is a similar situation in the electron roller coaster except that, instead of releasing a scream, the electrons release their converted light and, as they do so, plunge from a high energy state back to their original state. In the fairground roller coaster, the scream we let out as we fall to the ground is short because it is generally a short distance from the top of the roller coaster to the bottom. In the electron roller coaster, the distance the electron falls, or the energy gap – which varies from substance to substance – determines the colour of the emitted light [*4]. To put it another way, the energy gap can be artificially changed to vary the colour of the light emitted by changing the substance used to make the LED.

The analogy of the roller coaster may be unusual, but has it helped your understanding of the process of material light emission?

It was 1962 when the concept of energy gap was put to into practice and the first light emission by a compound semiconductor – direct electricity-to-light conversion – was achieved using gallium and arsenic.

[*3] You might think that the positively charged atom nucleus and the negatively charged electron would attract one another and that the electron would be drawn in to the nucleus. However, in actual fact, this does not happen. The electrons spin around the shells at great speed centering on the nucleus and are not attracted to the positive nucleus.

Making LEDs

We have now covered the basics of light emission. As you can probably imagine, creating LEDs such as those used in printers is all about producing a state in the substance in which there is an energy gap, with large numbers of electrons carrying a high level of energy.

When the electrons revert from a high energy state to their original state, well-like spaces, technically known as “holes”, come into play. More detail is given about holes later on.

The process of LED light emission is easy to explain, but difficult to produce. OKI’s world-leading LED technology, and indeed Oki Data’s LED printers, have come about thanks to the efforts of our colleagues who developed this technology.

Figure 5 is an enlargement of the light emitting part of an LED used in Oki Data’s color printer. Within the millions upon billions of atoms in each gallium-arsenic-phosphorus crystal, you can see the red light electrons releases as they return from a high energy state to a low energy state.

Digital LEDs used in color printer In the areas emitting red light, successive electrons and holes join up to produce light.
(Enlarged 300 times).

Figure 5
LED light emission

The semiconductor laser used in the laser printers is one type of LED. In the semiconductor laser the light source produced by the LED is used as energy to induce successive emission of light which is then reflected within a special structure, to line up the waves of light in the same position (in technical terms this is known as coherent light which means that the waves of light are all in phase with each other). The light is then reflected out of the laser.In comparison to the LED, the structure of the laser is very complicated, making it impossible to form an array structure (elementsarranged in a row). We will now go on to take a look at the process of light emission in more detail. I will try to make

it as simple as possible, although some technical details will be included. After reading this, you should be able to understand how LEDs emit light and gain further insight into the mysterious world of the atom.

[*4] As light is an electromagnetic wave, the speed (frequency) of the light waves determines the different colours of light –red, blue, yellow, green etc.
Strictly speaking, the colour of light is determined by the following formula, known as Bohr’s frequency conditions. In Fig.4, if the high energy state is **E2**, the low energy state **E1** and the energy gap **E**, then
$\mathbf{E=E2-E1=h\nu=hc/\lambda}$
(**h**: Planck’s constant 6.6262 x 10^{-34} JS [joules/sec]
ν: light frequency [sec^{-1}], **c**: light speed
λ: wavelength of emitted light)
h is Planck’s constant and is fixed, so by artificially changing **the energy gap (E)**, ν (light frequency) changes, enabling the colour of the light emitted to be changed. For more detail refer to reference documents (2) and (3) .

From the World of Atoms to the World of Semiconductors*5

As you now understand the essence of light emission in the world of atoms, we can at last go on to look at the LED light emission process in detail. (An LED is a gallium (Ga), arsenic (As) and phosphorus (P) crystal. Strictly, it is a type of **compound semiconductor**, but we shall shorten this to semiconductor).

Figure 6 shows an atom model of gallium (Ga), atomic number 31. (Refer to *6 for an explanation of the atom model). As described in “Light emission from substances”, **electrons rotating in the outer shell furthermost from the atom nucleus are not greatly influenced by the nucleus and can easily become free**. Therefore, it is the elements in this outer N-shell that we should turn our attention to. (The three shells closest to the atom core are known as K shell, L shell, and M shell. Electrons in these shells are strongly influenced by the nucleus of the atom and are shown in the diagram with subdued faces). Gallium has an atomic number of 31 because there are 31 electrons circulating the atom nucleus. All atoms have 2, 8 and 18 electrons in the respective shells from the atom core, and in the case of gallium, there are 3 electrons in the outermost shell. (Electrons in the outer shell: 2+8+18=28, 31-28=3). We shall now concentrate on electrons in this outermost shell as indicated in figure 7.

These electrons can move around freely and are represented with active faces.

Next is **arsenic (As)**, atomic number 33. It has a total of 33 electrons and has 5 electrons in the outer shell, 2 more than gallium. An image of this is shown in figure 8. (This figure shows only electrons in the outermost shell). An important point to note is that **8 electrons in the outer shell is an extremely stable state** for an atom to have. Gallium has only 3 electrons in the outer shell, so it is 5 electrons short. Arsenic has 5 electrons in the outer shell, so it is short by 3 electrons. Now let us take equal portions of gallium and arsenic and mix them together to form a crystal (precision technology is required to form crystals, but we’ll skip the details for now). If successful, the electrons in both elements bond together as shown in Figure 9, and a gallium arsenide crystal with **8 electrons in the outer shell** is formed. Figure 9 shows a width and length of only 4 atoms for illustration. The electrons are shown in different colours depending on which nucleus they belong to, but they are actually the same whatever the nucleus type. A real crystal is made up of this structure extended in 3 dimensions. If you recall figure 3(a), **atoms are 3-dimensional**. Billions and trillions of atoms link up endlessly to form a crystal that can eventually be seen by the human eye.

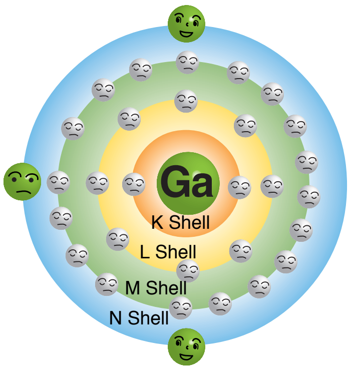


Figure 6
Gallium (Ga) Atom Model, Atomic Number 31

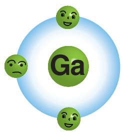


Figure 7
Simplified Gallium (Ga) Atom Model (Outermost shell has 3 electrons)

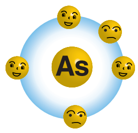


Figure 8
Simplified Arsenic (As) Atom Model (Outermost shell has 5 electrons)

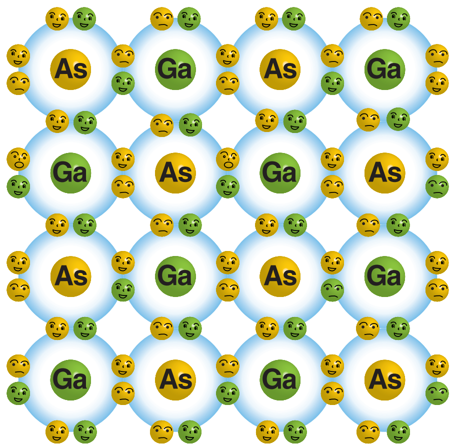
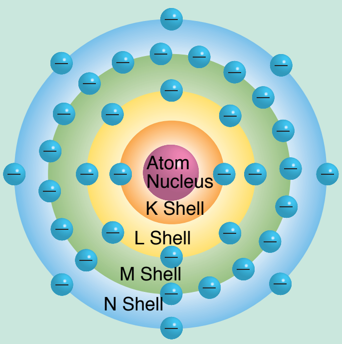


Figure 9
Gallium Arsenide Crystal Model (Covalent Bond)



- Each shell of electrons rotates in concentric circles around the central atom nucleus.
- Shells are named as shown in the diagram on the left, starting with that closest to the atom nucleus.
- Only a maximum fixed number of electrons can enter each shell:
  K Shell : 2 electrons L Shell : 8 electrons
  M Shell : 18 electrons N Shell : 32 electrons
- The shell furthest from the nucleus is known as the outermost shell, and electrons in this shell are called valence electrons.
- If there are 8 electrons in the outer shell, a stable state can be maintained (in the case of M Shell and N Shell).
- As outer shell electrons are distanced from the atom nucleus, they are not restricted by the atom nucleus and can easily become detached from the atom and move around freely.
- The energy held by the electrons in each shell has random (not continuous) values.

***6 Detail of Figure 2 Atom Construction Model (Bohr’s Atom Model)**

*5 Refer to *8 for an explanation on semiconductors

Increasing Electrons and Holes for Light Emission

If you recall, in “Light emission from substances” I said that light emission requires electrons in high energy state and holes to receive these electrons. Here, I will explain the method of increasing such high energy electrons and holes. A tiny amount of a third element is mixed with the gallium arsenide crystal (figure 9) to form a new crystal. (This is known as **impurity doping**.)

Firstly, the technique to increase the number of electrons is to add tellurium (Te), which has atomic number 52 and has 6 electrons in its outer shell, as shown in figure 10. As a result, the tellurium **replaces some of the arsenic atoms**, as you can see in figure 11. However, because tellurium has **6 electrons in its outer shell, 1 more than arsenic’s 5**, there is **1 extra electron**. The energy held by this electron is high just like the energy at the top of the roller coaster in figure 4. Because this electron moves around freely within the crystal, it is known technically as a **free electron**. As explained earlier, electrons are negatively charged with electricity. Therefore, movement of electrons is equivalent to the flow of an electrical current.

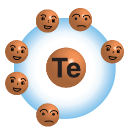


Figure 10
Simplified tellurium atom model (6 electrons in outermost shell)

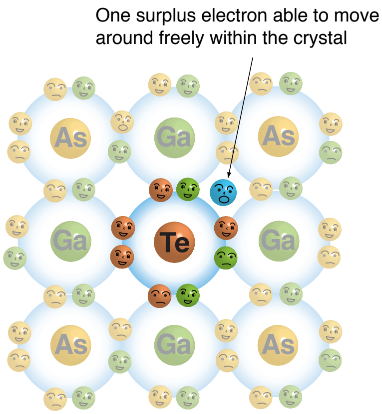


Figure 11
Model of gallium arsenide crystal with added tellurium → N-Type semiconductor

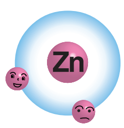


Figure 13
Simplified zinc atom model (2 electrons in outermost shell)

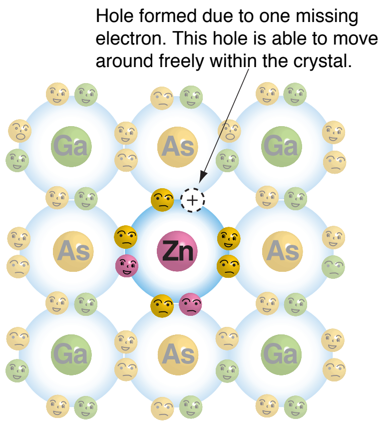


Figure 14
Model of gallium arsenide crystal with added zinc → P-Type semiconductor

At this stage, however, there is an important point to remember: **Electrons move in the opposite direction to the flow of an electrical current**. This is based on the convention that electrical currents flow from the battery’s positive terminal to negative, as illustrated in figure 12. However, it is interesting to note that at the time it was decided that the flow of an electrical current was from positive to negative, **electrons had not yet been discovered**. It was not until later that it was found that **electrons in fact flow in the opposite direction to electrical currents**, but it was thought to be too troublesome to change, and so the situation remains today. Therefore, electrical flow is from positive to negative, but **electrons move from negative to positive**.

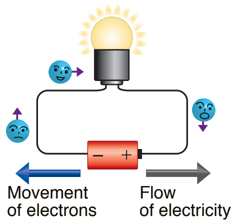


Figure 12
Electrical Current Flow and Electron Movement

To get back to the original topic, as the large numbers of (free) electrons existing within the crystal are negatively charged, in technical language, these types of crystal are known as **N-Type Semiconductors**.

And now for the technique used to increase the number of holes. We have said that there is **an extra electron in the N-type semiconductor**, as shown in figure 13, but to make a hole, the number of **electrons is reduced by 1**. Zinc (Zn), which has atomic number 30 and has 2 electrons in its outer shell, is added to the gallium arsenide crystal and **replaces some of the gallium atoms**. (Not the arsenic!) Zinc has only 2 electrons in its outer shell, one less than gallium, so it is **short by 1 electron**. When making an N-type semiconductor, there is 1 **extra electron**, but in this case, there is **1 electron missing**. Because of this, there are only 7 electrons in the outer shell instead of 8 (see figure 14). The hole is formed in this way. As the hole is created when the negative electron leaves, the hole is positive. In figure 15 you can see that when an active electron from the neighbouring atom jumps next door, it leaves a space in which a hole is formed. Holes move around freely within the crystal in a kind of domino-effect. Such holes with the ability to move in this way are known as **free holes**. Crystals which have large numbers of positive holes are called **P-type semiconductors**. We have now covered N-type semiconductors which contain vast numbers of free electrons, and P-type semiconductors, which contain huge quantities of holes. It is very interesting how the nature of each atom is cleverly utilized. Now let’s look into how N and P-type semiconductors are combined to emit light.

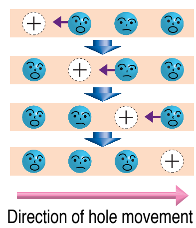


Figure 15
Direction of hole movement

Joining of P-type and N-type semiconductors

"Joining" here means sticking together, but it does not mean simply bonding with glue. What actually happens is that a P-Type semiconductor is formed (or grown) on top of an N-type semiconductor. Figure 16(a) shows a successfully joined P and N-type semiconductor. In technical terminology this is known as a P-N junction. In the diagram, (free) electrons are shown with a minus (−) symbol and (free) holes with a plus (+) symbol.

At a P-N junction, negatively charged electrons in the N-type semiconductor and positively charged holes in the P-type semiconductor attract one another, as figure (b) shows. This results in the holes spreading into the N-type semiconductor and the electrons spreading into the P-type semiconductor. This is a similar phenomenon to the spread of ink in water, and is called diffusion. Figure (c) shows that when the electrons and holes unite, they cancel each other out, forming a barrier, or depletion region. Once this barrier has been formed it acts as a wall and obstructs the to-ing and fro-ing of electrons and holes from either side.

Connecting a battery (power supply) to the P-N junction

As can be seen in figure (d), when the P-N junction is connected to a battery's positive and negative terminals, the barrier lowers[*7]. As the electrons are negative, they are attracted to the positive battery terminal and begin to move towards the P-type semiconductor across the weakened barrier.

What happens next?

As illustrated in figure (e), when the electrons invade the P-type semiconductor, they encounter and unite with the many holes existing within it and **release their energy in the form of light**.

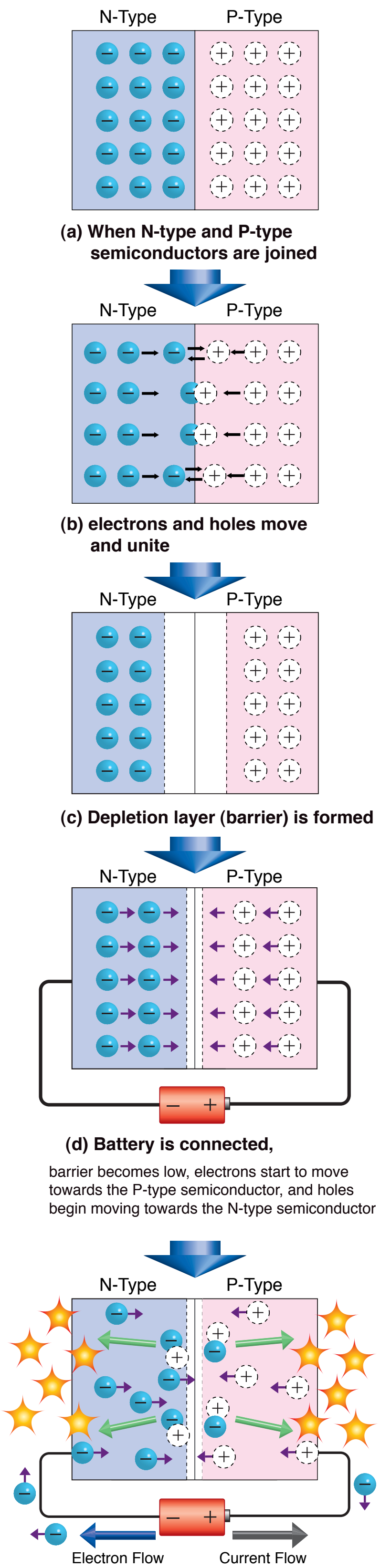
Likewise, the holes that invaded the N-type semiconductor meet up with the electrons that exist in huge numbers within the N-type semiconductor. These electrons then unite with the holes from the P-type semiconductor and **release their energy in the form of light**.

You may wonder whether this process might not cause the electrons in the N-type semiconductor to completely disappear. However, if you now recall that the **direction in which the electrical current flows is opposite to the direction in which the electrons move**, as figure (e) indicates, electrons are continuously supplied to the N-type semiconductor from the battery, so there is no danger of electron depletion.

On the other hand, electrons flow out of the P-type semiconductor in the direction of the battery. When these electrons leave the semiconductor (disappear), holes are formed, and this enables a continuous supply of holes to be made within the P-type semiconductor.

As electrons are continuously supplied by the battery, even though the electrons and holes unite and release light, they do not become depleted but continue constant light emission. If we refer back to "Light emission from substances": "the electron receives energy in the form of light, heat or electricity from an external source." The source of energy for electron light emission is supplied in this way by the battery (power supply).

[*7] To be more precise, when the barrier is formed, a positive diffusion potential occurs on the P-side of the junction and a negative diffusion potential on the N-side. As these diffusion potentials work in the opposite direction from the potential of the externally connected battery, the battery's power cancels out the diffusion potentials and this weakens the barrier.



(a) When N-type and P-type semiconductors are joined

(b) electrons and holes move and unite

(c) Depletion layer (barrier) is formed

(d) Battery is connected,
barrier becomes low, electrons start to move towards the P-type semiconductor, and holes begin moving towards the N-type semiconductor

(e) Light emission
Electrons that invaded P-type unite with holes and release light. Holes that invaded N-type unite with electrons and light is released.

Figure 16
Joining of N-type and P-type semiconductors and light emission

Energy held by electrons and light emission

In figure 4 on page 2, the process of light emission was explained by the energy held by the electrons and the atom roller coaster analogy. Figure 17 uses the same concept to explain the principle of P-N junction luminescence.

Figure (a) illustrates the state before the N-type and P-type semiconductors are combined. The N-type semiconductor is made of gallium arsenide with tellurium added to produce many extra (free) electrons. This is an equivalent state to electrons being raised to the very top of the roller coaster in figure 4.

Meanwhile, the P-type semiconductor, which is gallium arsenide with added zinc, has a huge number of (free) holes lacking electrons. Figure (b) shows N-type and P-type semiconductors joined together, or a P-N junction. As explained in figure 16, you can see that a barrier (depletion layer) has formed and the electrons are unable to move to the P-type semiconductor where the holes are waiting. Likewise, the holes are unable to cross the barrier and travel to the N-type semiconductor.

As Figure(c) shows, when the battery is externally connected, not only does the height of the barrier drop, but also the negative electrons are attracted to the positive battery charge and invade the P-type semiconductor, making a beeline for the vast number of holes existing there. Just like a plummeting roller coaster, the electrons start free-falling down into the pool of holes waiting below, and the stored **energy is released in the form of light** as the electrons and holes unite.

This may be easier to understand if you imagine the release of light as a scream from the electrons on the atom roller coaster when they plunge to ground level.

Likewise, when the barrier in the P-type semiconductor weakens, the holes are strongly attracted to the negative battery terminal and rush into the N-type semiconductor. Here the holes encounter the huge number of electrons, which then fall like a roller coaster releasing their energy as light as they unite. This energy for light emission is continuously supplied by the battery.

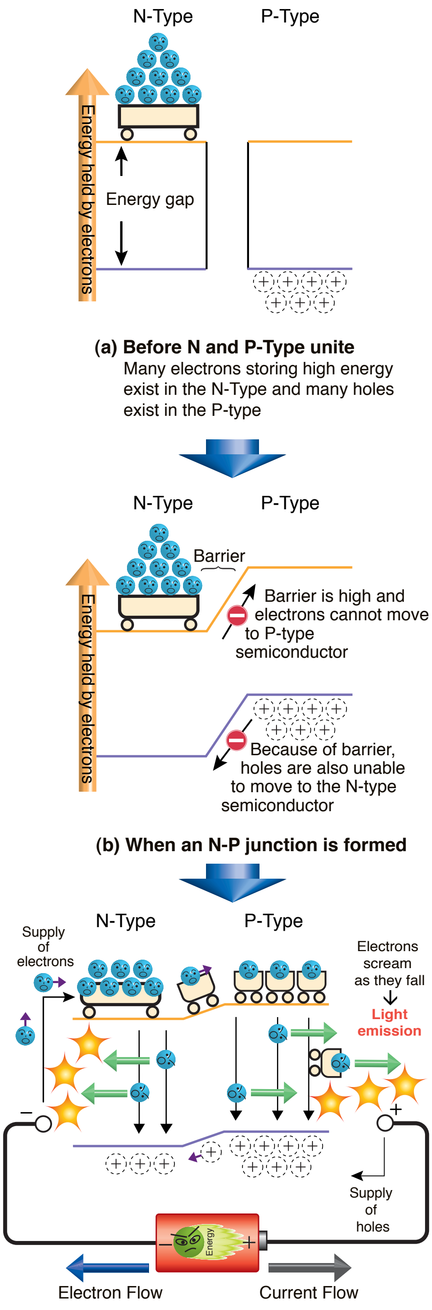
The above is a detailed account of the how light emission takes place. We have now covered the microscopic world of the atom, and the role of electrons. I hope this has helped you understand how an LED emits light.

The function of phosphorus (P)

I explained earlier that gallium (Ga), arsenic (As) and phosphorus (P) form LEDs. The actual role of phosphorus is to alter the amount of arsenic blended when creating a gallium arsenide crystal. Similar to arsenic, phosphorus also has 5 electrons in its outer shell and therefore replaces the arsenic. By altering the ratio of chemical elements used, it is possible to change the energy gap value (see 17a). By changing the distance electrons fall (see (c)), the required colour (frequency) of light can be obtained*[4]. LEDs ranging in colour from red to blue are already available. It is also possible to change the colour of emitted light by using different combinations of atomic elements, and this technology has also been put to practical use to increase the range of LED colours. The main colours of light emitted by different crystal constituents are shown in table 1. For further details please refer to references (2) and (3) given at the end of this issue.

Table 1 Main LED crystal materials and colour of emitted

Colour of emitted light	Crystal material	Peak wavelength λ (nm)	Main uses of light
Violet	InGaN	405	Lamp, display
Blue	InGaN ZnCdSe	450 489	Lamp, display
Green	InGaN GaAsP	520 555	Lamp, display
Yellow, orange	AlGaInP	570~590	Lamp, display
Red	AlGaAs	660	Lamp, display
Infrared	GaAsP AlGaAs GaAs InGaAsP	740 740 980 1550	Print head Print head Remote control, photo-coupler Optical communication



(c) When battery is connected externally

The barrier weakens, and the electrons in the N-type semiconductor invade the P-type semiconductor, unite with the holes and emit light.
The holes in the P-type semiconductor also move into the N-type semiconductor, unite with the electrons and emit light.
Electrons and holes are continuously supplied by the battery.

Figure 17
State of Energy Held by Electrons

As explained earlier, the LED is made of the main elements gallium (Ga), arsenic (As), and phosphorous (P). This type of semiconductor is known as **a compound semiconductor**. **Semiconductors** supporting the modern day electronics industry, for example, transistors and diodes, CPUs and LSIs - the central controllers of electrophotographic printers, and memory chips - all use silicon (Si), which has an atomic number of 14.

Why use silicon? Silicon is commonly used because it is the main constituent of common stone and both easier to handle and cheaper than gallium arsenide.

Gallium arsenide is the main LED material, but it is also sometimes used in high-speed transistors and LSI chips because the speed at which its electrons move within the crystal is approximately five times faster than in silicon. However, this is not yet commonplace.

Unfortunately low cost silicon cannot normally be used for light emitting LEDs. Please refer to references (2) and (3) for more details.

*8 Semiconductors, conductors and insulators

Familiar metals, such as iron, steel and copper contain many electrons which can move around freely (**free electrons**), and electricity can flow through them easily. Another way of saying this is that resistance of these substances as defined by Ohm's law is low. Such substances are known as conductors.

In contrast, insulators (such as glass and rubber) hardly conduct electricity at all because they do not contain any free electrons. Gallium arsenide and pure silicon crystals have few free electrons and holes and cannot conduct electrical currents well (this is known as an intrinsic semiconductor). By adding the dopants tellurium or zinc to gallium arsenide and boron or phosphorus to silicon, free electrons and holes are formed, and the substance changes into a semiconductor, which can conduct an electrical current. Semiconductors are so called because they are mid-way between a conductor and an insulator. Semiconductors are not like copper and steel, which have a low resistance to electricity, but by varying the dopant dose, the number of electrons can be increased or decreased (by increasing the number of holes). In this respect, the current flowing through the semiconductor can be adjusted and controlled easily, and this is a major characteristic of the semiconductor. Transistors, diodes, and of course LEDs used in electronic equipment cleverly utilize the movement of electrons and holes within the semiconductor to function as a kind of electricalswitch or emit light.

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