Foundations of Photovoltaics

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Abstract

The photoelectric effect is due to electrons being emitted from metal when it is exposed to solar radiation. Einstein explained the phenomenon using Max Planck's constant of thermodynamics to describe the energy of the ejected electrons. Continuing the work with this theory, Gilbert Lewis applied the term *photon* to the quantum of light. Photons have no mass, but they carry energy, and according to Einstein's famous equation $E=mc^2$, mass and energy are equivalent. The concept of wave-particle duality, in which light exhibits both wave-like and particle-like behaviors, had been studied in the 1800's by Thomas Young in his famous double-slit experiment and Arthur Compton's x-ray experiments, but was not fully explained until 1905 by Einstein. The first solar battery, developed in 1954 for space technology, successfully captured the emitted electrons to convert into usable electricity. Today, solar cells are effectively used in collected arrays to convert sunlight. However, more work is necessary to make the technology efficient and inexpensive.

In testimony before the U.S. Senate Commerce Committee in 1974, Thomas Carr explained that "The word 'energy' incidentally equates with the Greek word for 'challenge'" (qtd. in Fields, 2001). The **challenge today is to employ renewable sources of energy, making them inexpensive and practical**. The number one source of renewable energy is the sun. With the current fears about the rapid consumption of fossil fuels, today's focus is on solar power. Our scientific and engineering knowledge needs to be poured into **novel approaches to photovoltaic technology.** The basis of all solar energy technology is the photoelectric effect. This is the phenomenon of light "jiggling loose" electrons on a metal surface, as first explored by Einstein. These electrons are captured in a circuit to provide the electricity for devices that we use daily. "Nearly 90% of electricity-generating solar panels sold today are based on the original practical solar cell technology of the 1970s, which employs crystalline silicon. But these cells are expensive to fashion. Other, newer technologies may prove to be cheaper to make and more efficient at converting sunlight to electricity…" (Fields, 2001, p. A16).

The Photoelectric Effect and the Nature of Light

Certain metals will produce a small electric charge when light is shined upon them. This is known as the photoelectric effect, which was first studied in 1839 by the French physicist Edmund Bequerel. Nobody truly understood how this was happening until Albert Einstein described how light can produce electric charges in 1905. It was for his study on light and the photoelectric effect that Einstein was awarded a Nobel Prize in physics (Knier, 2002). The photoelectric effect is defined as the "phenomenon of electrons being emitted from a metal when struck by incident electromagnetic radiation" (Weisstein, 1996). Metallic surfaces exposed to radiation above a certain frequency absorb the light and almost instantaneously emit electrons:

1. For a given metal and frequency of incident radiation, the rate at which photoelectrons are ejected is directly proportional to the intensity of the incident light.
2. For a given metal, there exists a certain minimum frequency of incident radiation below which no photoelectrons can be emitted. This frequency is called the threshold frequency.
3. Above the threshold frequency, the maximum kinetic energy of the emitted photoelectron is independent of the intensity of the incident light but depends on the frequency of the incident light.
4. The time lag between the incidence of radiation and the emission of a very small, less than 10^{-9} second. photoelectron is very small, less than 10^{-9} second.

("Photoelectric effect," 2008)

Quantum Hypothesis

In 1900, the German physicist Max Planck proposed that hot, or rapidly vibrating, matter gives off radiation, not as continuous waves, but in discrete packets known as "quanta." In working with thermodynamics, Planck made an assumption that energy is "made up of a completely determinant number of finite equal parts" (qtd. in Kragh, 2000). According to classical physics calculations, the total energy inside of an oven at a given temperature would have to be infinite, which is not possible (Greene, 2003, p. 88). In reality the physical size of the waves is constrained by the size of the oven and cannot exist as fractions, "the waves generated by the hot walls must have a *whole* number of peaks and troughs that fit perfectly between opposite surfaces" (Greene, 2003, p. 89). Furthermore, every wave carries the same amount of energy regardless of its wavelength. Therefore, "the minimum energy a wave can have is proportional to its frequency" (Greene, 2003, p. 92).

The energy associated with a given quantum is equal to the frequency of the vibration that produced that quantum multiplied by an integer, according to Planck's equations below:

$$E_{min} = hf$$

$$E = nhf$$

In the above equations, E_{min} is minimum energy, E is energy, h is Planck's constant (6.626176 x 10^{-34} J•s), f is frequency, and n is an integer (Davis, "Planck," 2002). Just a few years later, Albert Einstein used Planck's equation to describe the energy of ejected electrons. That energy depends on the frequency of light being shined on the metal.

Photoelectric Equation

Einstein took Max Planck's quantum hypothesis, which stated that energy is measured in discrete parts known as quanta: "This **quanta** of light energy soon became known as the '**photon**' (i.e. discrete like a particle) and led to the paradox that light behaved both as a continuous e-m wave…as well as a discrete particle/photon…" ("Quantum Physics: Max Planck," 1999).

Einstein extended the quantum hypothesis to explain what was happening during the photoelectric effect by formulating the equation below:

$$K_{max} = hv - W_0 = \frac{hc}{\lambda} - W_0$$

where

- K_{max} is the maximum kinetic energy of emitted electrons
- h is Planck's constant (6.626176 x 10^{-34} J•s)
- W_0 is the amount of work needed to separate an electron from the metal
- c is the speed of light (3 x 10^8 m/s)
- λ is the wavelength of the electromagnetic radiation
- v is the frequency of the electromagnetic radiation (Weisstein, Davis "Photoelectric").

"Einstein's explanation of the photoelectric effect won him the Nobel Prize in Physics in 1921" ("Photoelectric effect," 2008). Einstein's work referred to "light quanta," which were later dubbed "photons" ("Photoelectric effect," 2008).

Photons

Continuing the work with this theory, Gilbert Lewis applied the term *photon* to the quantum of light in 1926. Some of the properties of photons are that they have no mass, only energy, but they move at exactly the speed of light in a vacuum. They also have momentum, but paradoxically, momentum is described as mass times velocity. Photons have no mass, but they carry energy, and according to Einstein's famous equation $E=mc^2$, mass and energy are equivalent (Suplee, 1999, p. 45).

Along with momentum, photons can have particle-like interactions with other particles such as electrons, as seen the Compton effect (Jones, “What is a Photon?,” 2009).

Compton Effect

This phenomenon was discovered in 1895 by American physicist Arthur Compton while working with X-rays. Compton bombarded graphite blocks with X-rays and observed how they scattered while in transit. He found that the X-rays’ frequency became as much as 7% lower when they were deflected by a large degree. What was happening was that the X-ray photon was striking an electron and bouncing off. When a photon struck an electron, it transferred momentum to the electron, causing the electron to start moving. The photon’s path would be bent, and it would result in the photon having a lower frequency. This phenomenon could not be described with the classical concept of radiation, though it was described accurately with the quantum hypothesis as devised by Planck and Einstein (Suplee, 1999, p. 44).

Double-Slit Experiment

While the Compton effect and the photoelectric effect both rely on the particle-like property of light, other phenomena show that light as a wave should not be discounted. The famous double-slit experiment by Thomas Young in 1801 can only be described correctly if light is a wave. The experiment consists of a single slit in a screen that could focus sunlight. Then another screen with two slits was placed some distance away from the first screen. When light was focused through both screens, interference patterns in the form of dark and light bands appeared on the far wall, as seen in Figure 1 below. Young realized that the interference patterns could only occur if light behaved as a wave (Davidson and Parry, 1998).

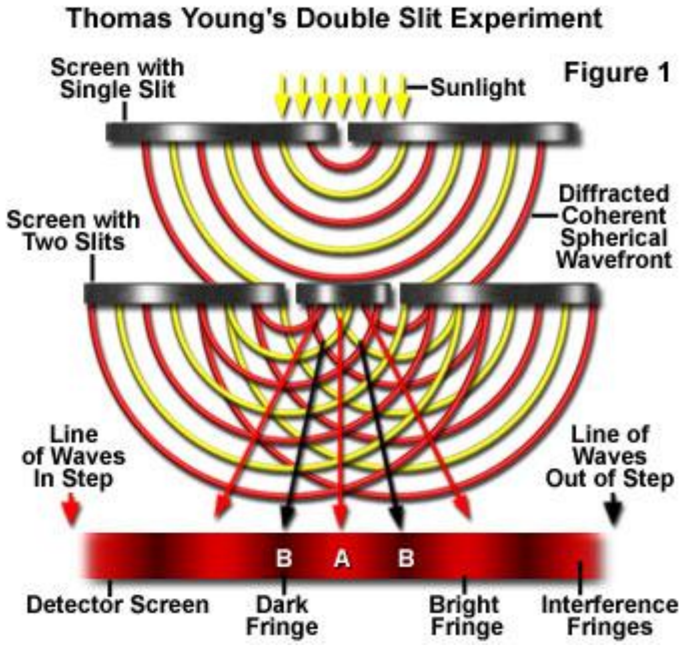

Figure 1: The double slit experiment showing how light behaves as a wave (http://micro.magnet.fsu.edu/primer/java/interference/doubleslit/index.html).

Quantum Version of the Double-Slit Experiment

Scientists were puzzled over why light has particle-like behavior as well as wave-like behavior, depending on the experiment. When the technology became advanced enough to emit one photon at a time, the double-slit experiment was repeated with this technology. Oddly enough, the interference pattern still occurred, even though only one photon was being emitted at a time. While this helped to confirm the wave-like nature of light, it was also confusing. Later it was found that when a measuring device is placed at the slits, the interference pattern did not occur. Instead, the pattern became one of randomly scattered dots instead of interference, much like what would be expected if light behaves as a particle. When the measuring device was removed, the interference pattern reappeared. To this day, it is not known why measuring the position of the particle, whether it is a photon, electron, or an entire atom, causes the interference pattern to disappear (Jones, “Quantum Version,” 2009).

Wave-Particle Duality

In order to properly explain light, however, one must use both the wave and particle descriptions of electromagnetism. The concept of wave-particle duality comes up when talking about light because of the wave-like and particle-like behaviors exhibited by photons (“Wave-Particle Duality,” 2009). When it comes to photovoltaics and solar energy, the particle nature of light is needed because of the photoelectric effect that is the foundation of all photovoltaics (Suplee, 1999, p. 45). Figure 2 below shows photons jiggling loose electrons from a metal plate.

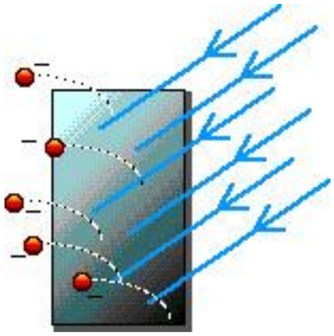

Figure 2: Photons (blue arrows) causing electrons (red circles) to be ejected from a metal plate (http://www.ux1.eiu.edu/~cfadd/1160/Ch28QM/Images/image03.gif).

Photovoltaics

While the photoelectric effect was successfully explained in 1905 by Albert Einstein, the first photovoltaic unit was developed by Bell Laboratories in 1954. However, it was too expensive at the time, and it was only six percent efficient (“The Solar Battery (Photovoltaics),” 2009). In the 1960s during the space race, solar technology improved, and the cost went down. This is because solar energy is abundant in space, and solar cell technology was perfect for satellites being sent into space. It took the energy crisis of the 1970s to push the technology over the edge and make it gain fame as a potential source of alternative power on Earth rather than just in space (Knier, 2002).

How Photovoltaics Work

Figure 3 below is an illustration of a basic solar cell. The semi-conductive material is treated by doping to induce an electric field that causes one side of the semiconductor to be negatively charged and the other side to be positively charged. If the semiconductor is part of a circuit with conductors, such as metal wires, touching both the positive and negative sides, then the electrons that are jiggled loose by photons from the sun will be captured along the negative side and sent through the circuit via the conductors (Knier, 2002).

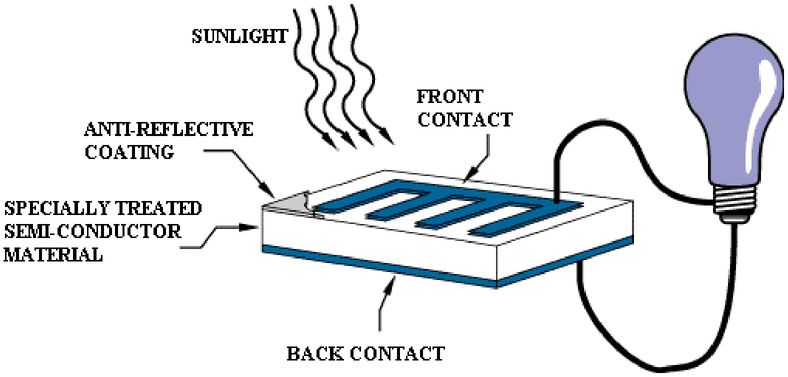

Figure 3: A basic photovoltaic cell connected to a light built in an electric circuit (http://science.nasa.gov/headlines/y2002/images/sunshine/cell.gif).

Multiple photovoltaic cells can be wired together to form what is known as a photovoltaic, or solar, module. Solar modules are designed to produce a certain amount of voltage, such as 12 volts, but the electric current depends on the amount of light that hits the module. Modules can then be wired together to form large solar arrays that produce vast amounts of electricity for society (Knier, 2002). Figure 4 below shows how photovoltaic cells form modules and how modules form arrays.

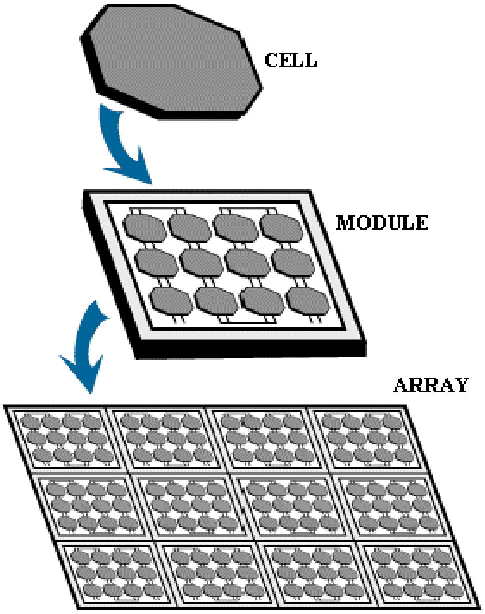

Figure 4: How photovoltaic cells can be arranged to form photovoltaic modules and arrays (http://science.nasa.gov/headlines/y2002/images/sunshine/array.gif).

An example of the use of a solar array is found in the Mary Ann Cofrin Hall, built in 2001, at the University of Wisconsin-Green Bay. (See Figure 5 below.) "Two hundred and fifty-two 43-watt, thin-film photovoltaic modules were installed in a glass curtain wall…" ("Photo Gallery," 2007). In order to implement the power generated by the photovoltaics, a power inverter, which converts direct current into alternating current, was installed in an electrical junction box ("Energy Features," 2007).

Figure 5: The finished photovoltaic wall at Mary Ann Cofrin Hall (http://www.buildingsolar.com/visionglass.jpg).

Efficiency of Photovoltaic Cells

While the first photovoltaic cell was around 6% efficient, advances in photovoltaic technology have increased its efficiency. In 1961, physicists William Shockley and Hans Queisser calculated that the maximum theoretical efficiency of a single-junction solar cell working without concentration of sunlight, known as one sun, is approximately 31%. The maximum theoretical efficiency, according to thermodynamics, of any photovoltaic cell under one sun conditions is approximately 68% ("Solar Photovoltaics," 2007, pp. 9-10).

The 31% efficiency was calculated for semiconductors that have bandgaps in the range of 1.25 eV (electron volts) to 1.45 eV. A bandgap is the energy required to move an electron from a lower band to a higher band, in this case from the valence band to the conduction band in a semiconductor. The magnitude of the bandgap is important when dealing with photovoltaics as photons with energies that are lower than the bandgap will not move electrons. The photons that have higher energies will be lowered to the maximum bandgap energy, and the rest of the energy will be lost as heat (Girifalco, 2009; Nozik, 2003, p. 3).

Conclusion

While the efficiency of photovoltaic technology is still a subject to be explored, the foundations of photovoltaics are rooted in the foundations of physics researched by Planck and Einstein. The photoelectric effect depends on the quantum duality of light as it operates as both a wave and a particle. Capturing the energy in order to convert it into usable energy as electricity holds much promise for the future. A thorough understanding of the process, followed by much experimentation to make efficiency and inexpensive solar cells is the energy challenge today.

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