100 Years of Light

Einstein's 1905 article heralded the science of photonics and its sweeping technological impact.

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Simply put, photonics is the applied science of light energy. But although "photonics" may not be a household word, this field has in fact had an enormous impact on our daily lives. Its products include a wide array of component technologies such as lasers, fiber optics, image sensors, light emitting diodes, and photomultiplier tubes. These may or may not be familiar, but the systems that rely on them certainly are: TVs and DVD players in our living rooms; photocopiers and laser printers at the office; barcode scanners at the supermarket; and x-ray systems in hospitals and airports. Photonics technology is everywhere.

So given its ubiquity, it seems natural to ask: How did photonics come about?

Since many of its applications deal with lasers, one answer could be that photonics started in 1960 when research scientist Theodore Maiman generated the first working laser from a synthetic ruby crystal. Or we could go back to 1926, when the term "photon" was coined by chemist Gilbert Lewis to denote the smallest unit of radiant energy. A third answer is that photonics actually came about a century ago with the birth of the photon concept itself, thanks to the great Albert Einstein.

In this brief overview, we will look at Einstein's contribution to photonics and also at how photonics has contributed to the benefit of humankind.

Figure 1. Photomultiplier tubes come in various shapes and sizes.

Einstein's pioneering work

While many people assume that Einstein won the Nobel Prize for his theory of relativity, the truth is that he received the award for an earlier work, "On a Heuristic Viewpoint Concerning the Production and Transformation of Light," published in 1905. In this paper, Einstein made a connection between the behavior of radiation filling a cavity and of an ideal gas filling a given volume. In both cases, entropy varies in the same way: the smaller the cavity or volume to be filled, the lower the entropy of the system. It is therefore possible, Einstein claimed, that electromagnetic radiation is similar to gas in that it is composed of particles. He called these particles "light quanta."

Einstein's concept of light as a wave carrying quantum particles was a radical departure from the conventional theory of the day, which postulated light as being the wave-like oscillations of electromagnetic fields. However, the light quanta description was a far better match for empirical evidence. The experiments in question were Philipp von Lenard's tests of the photoelectric effect. Stated roughly, the photoelectric effect refers to the emission of a current of electrons from a metallic surface upon the exposure of this surface to light. The effect varies depending on the amount of illumination, the frequency of the light source, and the type of metal used. In his experiments, von Lenard observed that while the *number* of electrons emitted from a metal plate bathed in ultraviolet light varied proportionally with the intensity of the light, the *kinetic energy* of the electrons did not. Instead, what did affect the kinetic energy of the electrons was the frequency of the light. Such observations could not be explained by conventional wave theory.

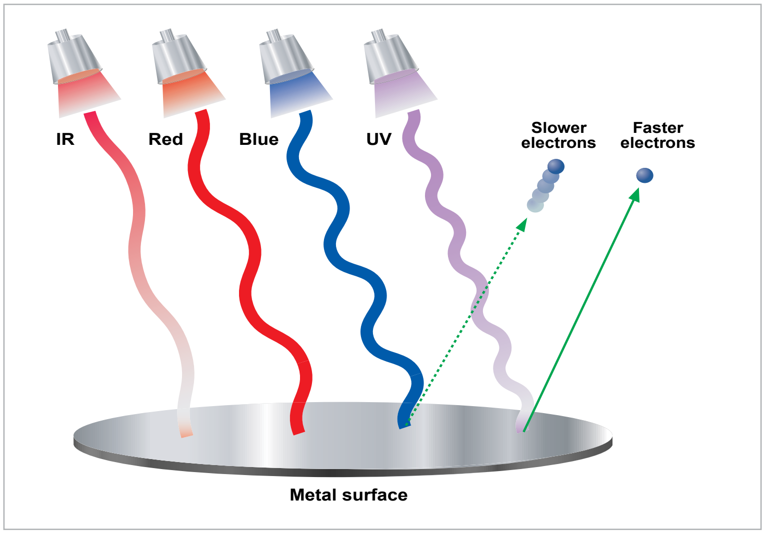

Figure 2. In the photoelectric effect, the kinetic energy of emitted electrons varies with the frequency of light.

Einstein, on the other hand, did have a viable account, expressed mathematically like so: $E = hf$.

This equation is true to Einstein's mixed interpretation of light in that E denotes the energy of particles; f denotes frequency, a property of waves; and h is Planck's constant, a number determined by Max Planck to calculate the amount of energy in each quantum. Applying this formula to the photoelectric effect, Einstein predicted that the maximum energy of the emitted electrons must vary linearly with the frequency of the light source. This prediction, which fits squarely with von Lenard's results, was experimentally validated by Robert Millikan in 1915.

It is thus fair to say that Einstein, as the first person to present a formal description of the wave-particle duality of light, made a landmark contribution to the field of photonics.

Our understanding of light has continued to evolve ever since. We have learned that photons have no rest mass, but travel at the speed of light and carry energy. Also, in terms of particle physics, we assume that the photon is one of the elementary particles of nature—a type of gauge boson. But perhaps more importantly, in the world of applied science, we have learned how to harness the power of photons for the technological advancement of mankind. Applied photonics is primarily involved in a broad range of the electromagnetic spectrum from infrared to visible light to ultraviolet to gamma rays. In what follows, we turn to real-world applications that involve the transmission, detection, and modulation of light.

Semiconductor manufacturing

Quality of life improved radically in the twentieth century thanks to the growth of the electronics industry. Therefore, one way to assess the importance of photonics is to understand its central role in this enterprise. Inside every piece of advanced electronics equipment, we find integrated circuits (IC). And inside every factory that manufactures these integrated circuits, we find a photonics-based process at work.

Photolithography is a process used in IC fabrication to transfer the circuit pattern from a photomask to the surface of a metal-coated silicon wafer. Basically, a laser is transmitted through the openings of the photomask to expose a photosensitive chemical compound, called a photoresist, that has been applied on the wafer. The exposed photoresist is then hardened and removed, leaving only the circuit pattern on the metal. In a complex integrated circuit, a wafer may be put through this photolithographic process dozens of times before it is completed.

The details of the process are more intricate. First, the silicon wafer is prepared on a wafer track system. An ultra-thin layer of conductive metal is applied on the surface of the wafer, followed by a layer of liquid photoresist on top of the metal layer. The photoresist is deposited on the wafer as it is being rotated at high speeds, which determines the thickness of the photoresist. At this point, the wafer is heated once before it is transferred to an exposure system called a stepper. It is here that the circuit pattern is projected onto the wafer.

The photomask itself is imprinted with the final circuit pattern, which is originally generated from a computer file, and is transparent only in the areas that the laser light should pass through. In this way, the photoresist can be hardened as desired through selective exposure. The stepper illuminates the photomask with laser light, such as 250 nm ultraviolet rays. The light then passes through a reduction lens system to focus the circuit pattern even further. When the light finally hits the wafer, the photoresist undergoes chemical reactions specific to the wavelength of the laser light. Afterward, the wafer is removed from the stepper and placed back on the wafer track system, where the photoresist is then developed, solidified through heating, and removed from the wafer. Ultimately, what remains on the wafer is a layer of metal in the pattern of the photomask.

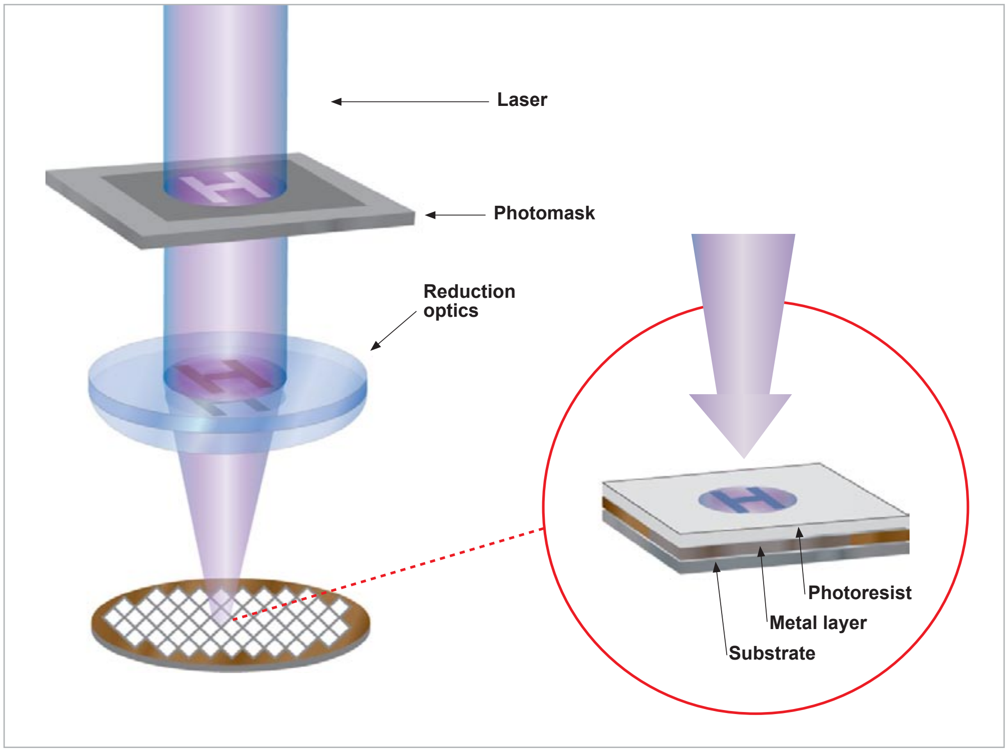

Figure 3. Miniaturization and transfer of a pattern through photolithography.

Another aspect of IC fabrication in which photonics plays a part is failure analysis. For example, a thermal emission analysis machine is equipped with detectors that are sensitive to temperature abnormalities on manufactured IC chips. These detectors, working in conjunction with an infrared confocal laser, enable the machine to quickly and precisely locate problems such as short circuits on unsuitable chips. This process of failure identification is essential for determining the causes of failure in a manufacturing system, which in turn contributes to the development of more reliable products.

Cancer diagnosis and treatment

The detection and transmission of light also serve a vital function in the medical treatment of cancer. One example of this is found in positron emission tomography (PET), a type of nuclear medical imaging in which radioactive molecules (i.e., positron emitters) are introduced to the patient's body as a means of scanning metabolic processes. The output of a PET scan is a three-dimensional image of blood flow in a targeted area within the body, at a resolution that is near molecular level. This information is extremely helpful in diagnosing cancers at an early stage, when treatment can be most effective.

The basic process of a PET scan is as follows. First, a glucose solution that contains a short-lived radioactive tracer isotope is administered to the patient. The patient then waits for this solution to accumulate in the targeted tissue area. Next, the patient is placed within an imaging scanner that surrounds him or her on all sides with a ring of gamma ray detectors. When the tracer decays, it emits a positron; the positron then reacts immediately with an electron, and this reaction produces two gamma ray photons that move in opposite directions from each other. The gamma ray photons are detected within the scanner by photomultiplier tubes, which amplify the signal to facilitate the plotting of the gamma ray's exit points. This data is used by the scanner to construct a three-dimensional image that displays where the tracer has become concentrated. The brightest parts of the image correspond to areas of highest tracer concentration, and may indicate the presence of rapidly metabolizing cancer cells.

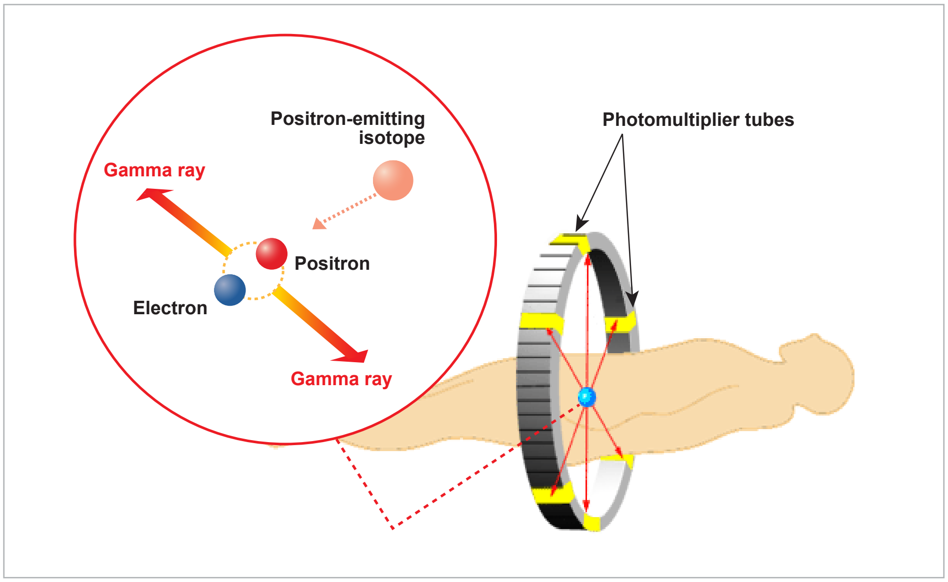

Figure 4. Gamma ray emissions within a PET scanner are detected by PMTs.

If cancerous tissue has been detected, then photonics can also be used to fight the disease. Photodynamic therapy (PDT) has three major components: a photosensitizer, which is a chemical compound that is sensitive to a specific wavelength of light; a light source; and tissue oxygen.

The initial steps of a PDT procedure are somewhat similar to those of a PET scan. First, a metabolic precursor of the photosensitizer is administered to the patient. The patient then waits for cells in the target area to convert the precursor into the photosensitizer. At this stage, the tissue to be treated is exposed to a light that is of a suitable wavelength to excite the photosensitizer. If the treatment is for cancer cells in internal organs, light can be delivered via an endoscope or fiber optic catheter. Treatment is localized by illuminating only the tissue area that requires treatment. (Without illumination, the photosensitizer stays inactive.)

Now the chemical reactions begin. Light excites the photosensitizer, transforming it from a ground singlet state to an excited singlet state. The photosensitizer then undergoes intersystem crossing to become an excited triplet state, at which point it binds to nearby oxygen molecules—one of the few types of molecules in human tissue that exists in a ground triplet state. Next, energy is transferred from photosensitizer to oxygen molecule. This relaxes the photosensitizer to a ground single state and, in turn, energizes the tissue oxygen into an excited singlet state. Finally, the singlet oxygen will react aggressively to cancer cells and incite a process of cell killing. This procedure can be repeated over the term of treatment until the majority of cancer cells in the target area have been destroyed.

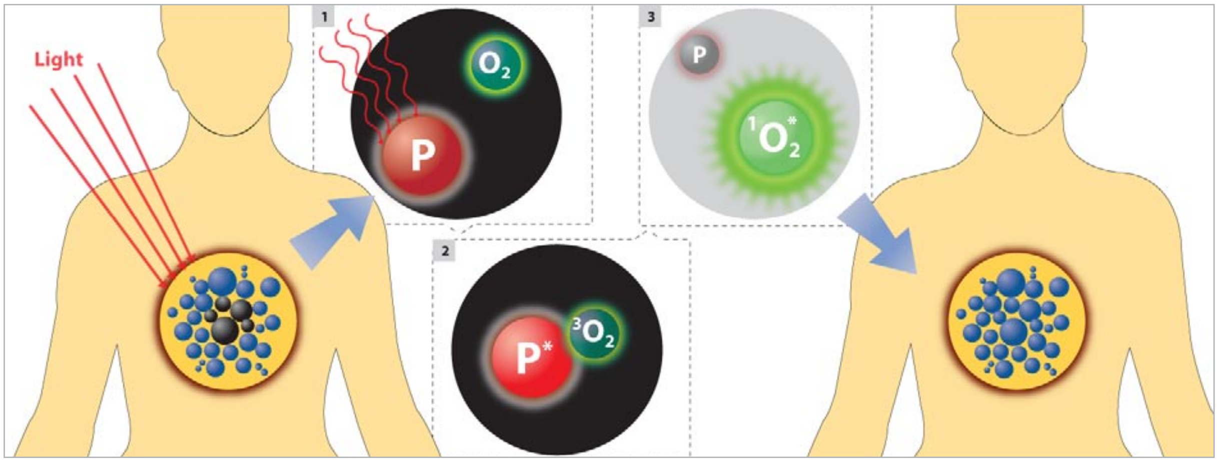

Figure 5. The chain reaction involved in photodynamic therapy. Cancer cells are denoted in black.

Other beneficial research

In addition to the ways described above, photonics contributes to the betterment of human society in many other spheres of life.

Efficient drug testing

Polarized light plays a key role in the automated systems used for high-throughput screening (HTS), in which dozens of pharmaceutical compounds are tested in a few minutes. A specialized machine prepares a tray with multiple portions of drug samples, and then illuminates and analyzes these samples. The amount of light reflectance measured in a sample can indicate, for example, that a particular drug is ineffective due to protein binding. This gives researchers immediate feedback on their hypotheses.

Secure communication systems

Most people have heard of fiber optics in relation to telecommunications. But there are also other, more advanced uses of photonics in this field. One such application is quantum cryptography. Messages encrypted by a physical technique of photon entanglement are literally eavesdropper-proof. This is because photons serve as a quantum carrier of information from point A to point B—and, as quantum physics tells us, we cannot measure a physical system at the quantum level without disturbing it. Any attempt at eavesdropping will leave traces.

Innovative agriculture

How do we build the world's most efficient greenhouse? This is an important question given the world population's ceaseless expansion and its growing need for food. Photonics researchers are currently developing a form of high-tech agriculture that has nothing to do with genetic modification. Crops are bathed in various types of light, and the results are monitored to determine which types of light and which irradiation methods achieve the greatest yield per unit of surface area. The objective is to design the best photonic environment for food cultivation.

Alternative energy

Solar power is widely advocated by environmentalists because it is clean and replenishable, unlike fossil fuels. The principle is simple: energy is generated by solar cells that, in essence, harness the photoelectric effect to convert sunlight into electricity. However, solar energy is not yet cheap enough for large-scale use. Further development of solar cell technology and their associated manufacturing processes will lead to more cost-efficient systems that, in the long run, may establish solar power as a major source of industrial energy.

This list is far from comprehensive, but hopefully it gives some idea of the expansive scope of photonics. There is seemingly no limit to where our continued research into light and our scientific ingenuity will take us. The next 100 years should be every bit as amazing as the first.