Quantum Wells as Light Sources

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Abstract

A quantum well is an extremely thin layer of low-bandgap semiconductor material sandwiched between thicker layers of high-bandgap material. The narrowness of this well creates discrete energy levels and changes electron-hole transport through the semiconductor. Utilizing quantum wells in modern light sources advances laser technology by widening the range of precise, achievable wavelengths. This optimizes wavelength control and tuning, increases modulation speeds, lowers energy loss, and reduces the overall system size. This research project examines the physics behind quantum wells and the importance of these advancements in modern technology.

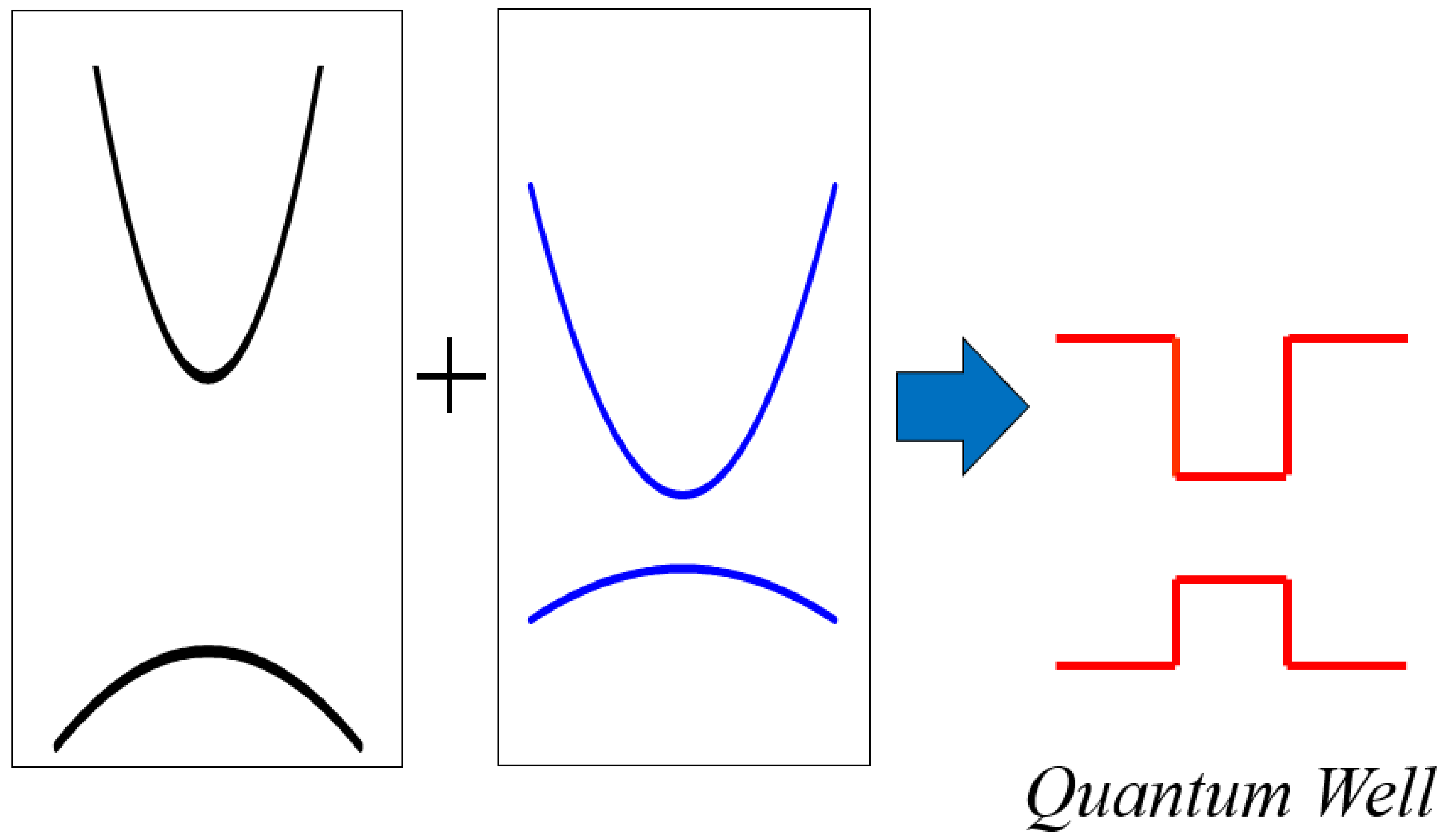

Figure 1. A diagram of the combination of semiconductors to create a quantum well, where the valence band is represented by the bottom line, and the conduction band is represented by the top line (in all depictions).

Semiconductor Physics

A semiconductor is a crystalline "insulator" with a small band gap. It is compromised of a valence band, which is normally filled with electrons at low temperatures, and a conduction band, normally empty of electrons at lower temperatures. The area between these bands is called a band gap, the size of which is directly proportional to the amount of energy needed for an electron to break free from the valence band and jump across to the conduction band. When an electron moves in this way, it leaves behind a positively charged "hole" behind in the valence band. Additionally, "doping" the semiconductor with specific impurities adds electrons or holes to the valence or conduction bands—this is called a p-n junction.

References

Miller, D. A. B. (1996). *Institute of Physics*.
R. Harris, *Modern Physics*, 2nd ed. (Pearson, Boston, 2008).

What is a Quantum Well?

A quantum well is created when a thin layer of low-bandgap semiconductor material (tens of nanometers wide) is sandwiched between two layers of higher-bandgap material. This makes a "well", where the high energy materials sit on either side of the low energy material. Electrons from the n-side of the semiconductor and holes from the p-side get pushed into the well and trapped when voltage is applied. Due to attractive forces, the electrons and holes form excitons, which then recombine to produce photons. The narrowness of the well increases chances of recombination, which generates more light than would occur without a quantum well.

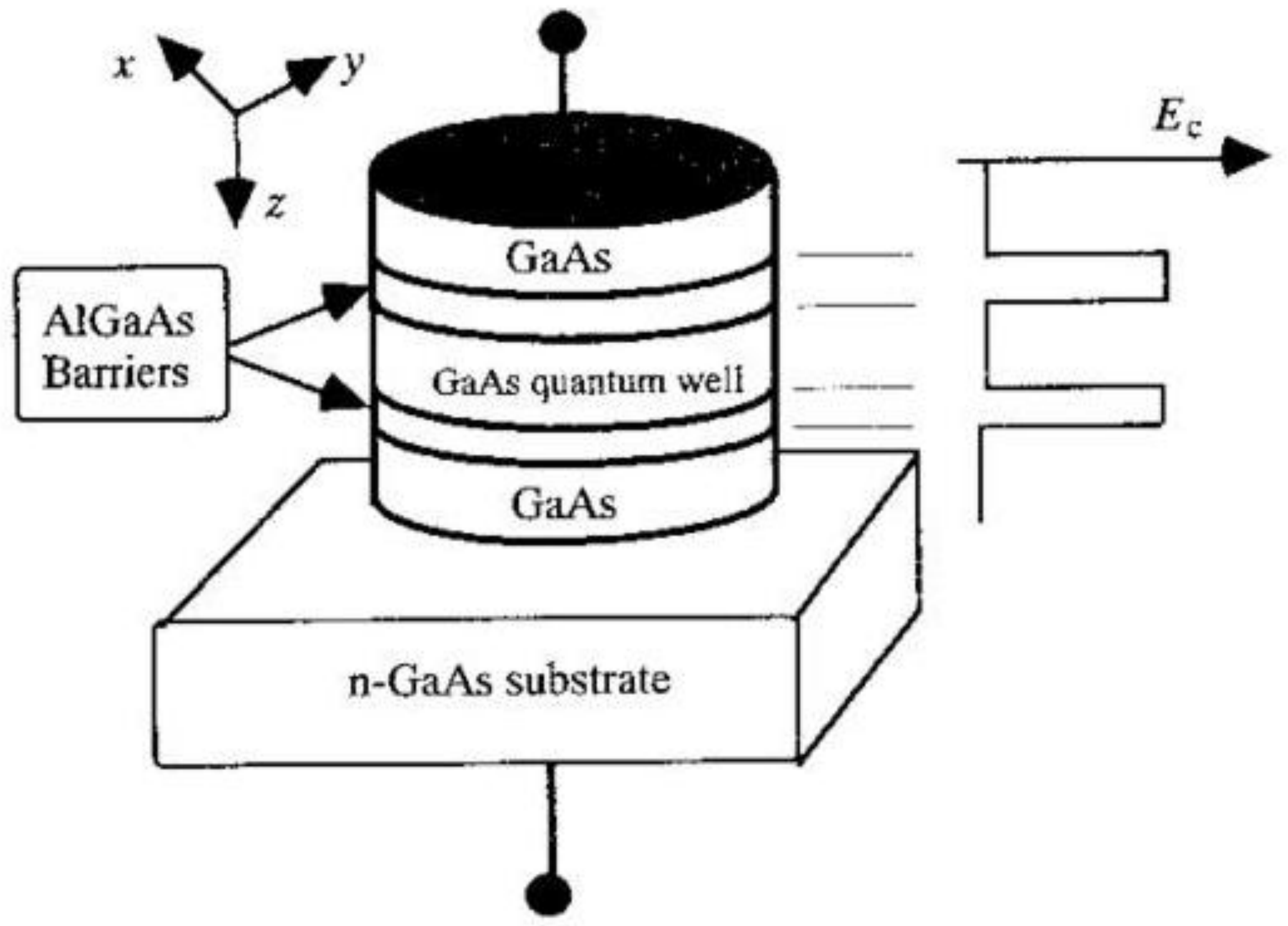

Figure 2. An illustration of the structure of a Gallium Arsenide (GaAs) quantum well, with the corresponding energy diagram on the right. Note that rotating the energy diagram 90 degrees shows a depiction of the GaAs quantum well comparable to Figure 1.

Physics of Quantum Wells

The energy equation for a very deep well is:

$$E_n = \frac{n^2\pi^2\hbar^2}{2mL^2}, n = 1, 2, 3, \ldots$$

Where n is an integer and L is the width of the quantum well. Because energy in the well is quantized, and the following can be applied:

$$E \sim \frac{1}{L^2} \qquad E = \frac{hc}{\lambda}$$

From these two expressions, it can be seen that increasing the width of the well L, decreases the energy E of the photons and increases the wavelength, emitting longer wavelength light. Inversely, if L is decreased, E is increased and wavelength is decreased, emitting shorter wavelength light. The quantization of this energy produces well-defined wavelengths.

Quantum Wells in Laser Technology

In lasers, both ends of the semiconductor are cleaved, acting as mirrors for the photons to bounce between. These photons energize free electrons to combine with free holes, creating more photons in a process known as stimulated emission. Because of this, the threshold current and the power supplied to create photons is lower than in lasers without quantum wells—these lasers are more efficient. Additionally, an optical waveguide surrounding the quantum well increases optical gain through total internal reflection of light, amplifying fiber optic signals. Quantum well lasers also react faster to changes in current, resulting in higher modulation speeds (tens of GHz). Finally, the use of quantum wells in lasers greatly decreases temperature sensitivity, leading to better performance, stability, and reliability.

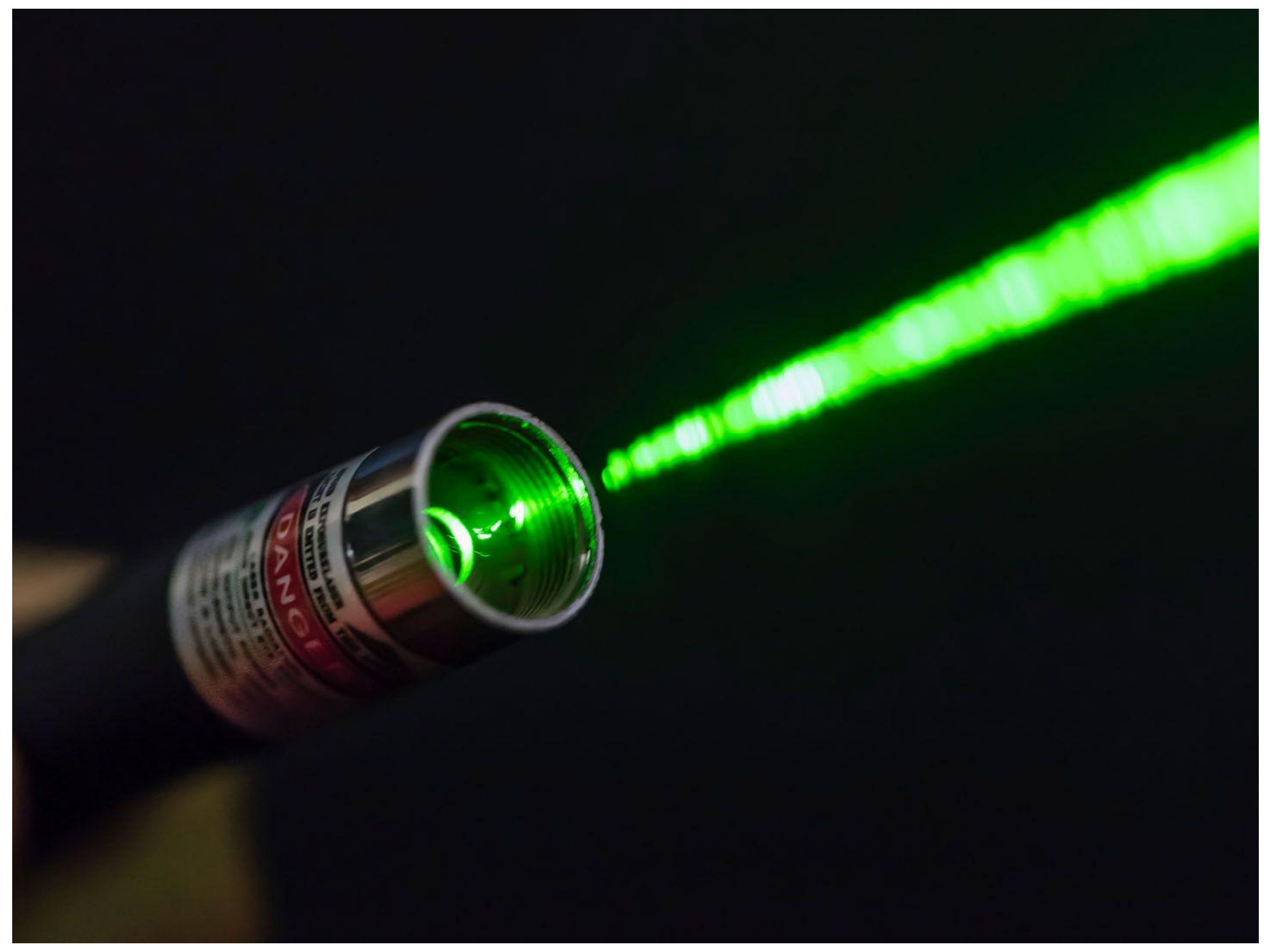

Figure 3. A green quantum well laser, which could be used in many of the applications listed below, including the observation of constellations in astronomy or other demonstrations.

Applications of Quantum Well Lasers

Quantum well lasers are used everywhere in modern day technology. Applications include:

- Fiber optics: requires specific wavelengths of light for transmission through fiber, making quantum well lasers valuable. This is the backbone of the internet and other telecommunications—without quantum well lasers, high-speed internet would not exist.
- Laser pointers: used for presentations, construction alignment, and astronomy observation.
- Barcode scanners: used to optimize asset management and logistics in retail, package delivery, and manufacturing
- Medical imaging: non-invasive techniques for visualization of tumors, blood vessels, and other tissues.
- LiDAR: a remote distance sensing technology used for topography, autonomous vehicles, and facial recognition
- Photonic integrated circuits (PICs): the future of computing technology. PICs are integral to the development of AI, autonomous vehicles, and 5G/6G infrastructures.

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