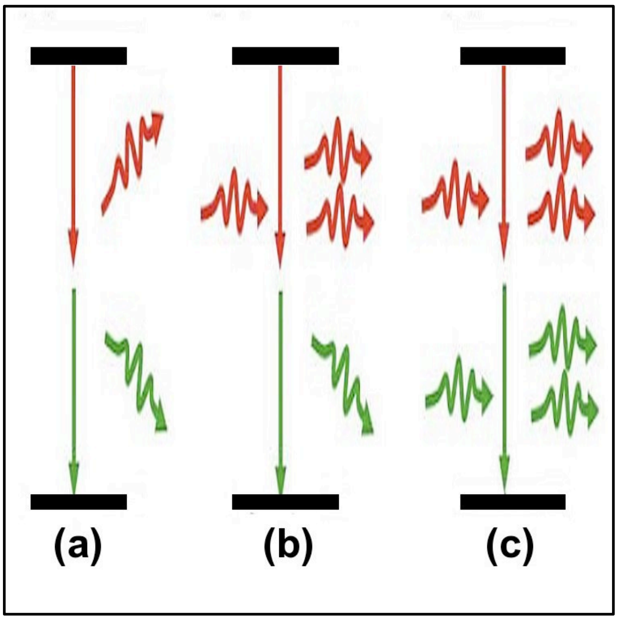
Semiconductor quantum photonics

by Alex Hayat
PhD from Technion, Istrael
2011 PhD Thesis Prize (Applied, joint with P. Ginzberg)

Semiconductor devices have been changing our every-day life. For example, the invention of the transistor more than half a century ago sparked a revolution that pushed out the cumbersome and energy-wasting vacuum tubes and kick-started the information age.



Diagrams of two-photon emission (TPE). (a) Transition diagram of spontaneous TPE. (b) Singly stimulated TPE (c) Fully stimulated TPE (TPG).

More recently compact semiconductor LEDs have been replacing the incandescent and fluorescent lamps for lighting. The last several decades have shown that there is much more to light sources than just lighting. Nowadays optics is the main carrier of the Internet data, and light sources employed for the fiber-optical communication infrastructure are compact semiconductor lasers. Ultrafast optical pulses, on the other hand, are widely employed today for characterizing physical and chemical processes that are too fast to be seen by any other means. These ultrafast lasers are also used for down-conversion of an ultraviolet photon into a pair of infrared photons in nonlinear crystals for realizations of quantum information processing, which takes advantage of the quantum nature of the microscopic world to implement extremely fast computers and absolutely secure communications. However, until now ultrafast lasers and non-classical light sources for quantum applications were based on bulky and energy-consuming systems, which must be pumped optically by intense laser pulses, limiting the widespread use of these applications.

In this Thesis, these ultrafast and quantum properties of light are realized in compact electrically-driven LED-like semiconductor devices by discovering a novel process of two-photon emission in semiconductors. In two-photon emission (TPE), electron transitions occur by simultaneous emission of a pair of photons. This phenomenon is important for astrophysics, and atomic physics. However, two-photon emission in semiconductors has not been observed, nor analyzed theoretically before. We demonstrated experimentally the first observation of two-photon emission in semiconductor devices, developed a corresponding theory and proposed this effect as an electrically-driven compact alternative to photon pair sources based on bulky schemes with optically-pumped nonlinear crystals.

We achieved spontaneous TPE (Fig. 1a), singly-stimulated TPE - where an incident photon stimulates the emission of a similar one and a spontaneous emission of a complementary photon (Fig. 1b), and fully-stimulated TPE that duplicates a pair of incident photons (Fig. 1c) - the source of nonlinear two-photon gain (TPG). TPG, in which photons are amplified in pairs, can be used for development of alternative kinds of lasers with unique properties including quantum squeezing and ultrafast pulse generation. Previously, TPG was demonstrated in atomic systems in maser-like configurations with very low efficiencies and optical pumping. Achieving two-photon gain in solids, and in particular semiconductors, is similar to the transition from the maser to the laser diode, with the benefit of higher efficiencies, miniaturization, and electrical pumping. First observations of electrically-pumped TPG in semiconductor waveguides were demonstrated here experimentally, and employed for ultrafast optical pulse compression.

Observations of TPE presented here, pave the way for future integrated quantum circuits, while the demonstrated implementation of TPG in electrically-driven waveguides may become a compact electrically-driven alternative to the conventional optical parametric oscillators and femtosecond lasers.