Physicists develop new design for fast, single-photon guns

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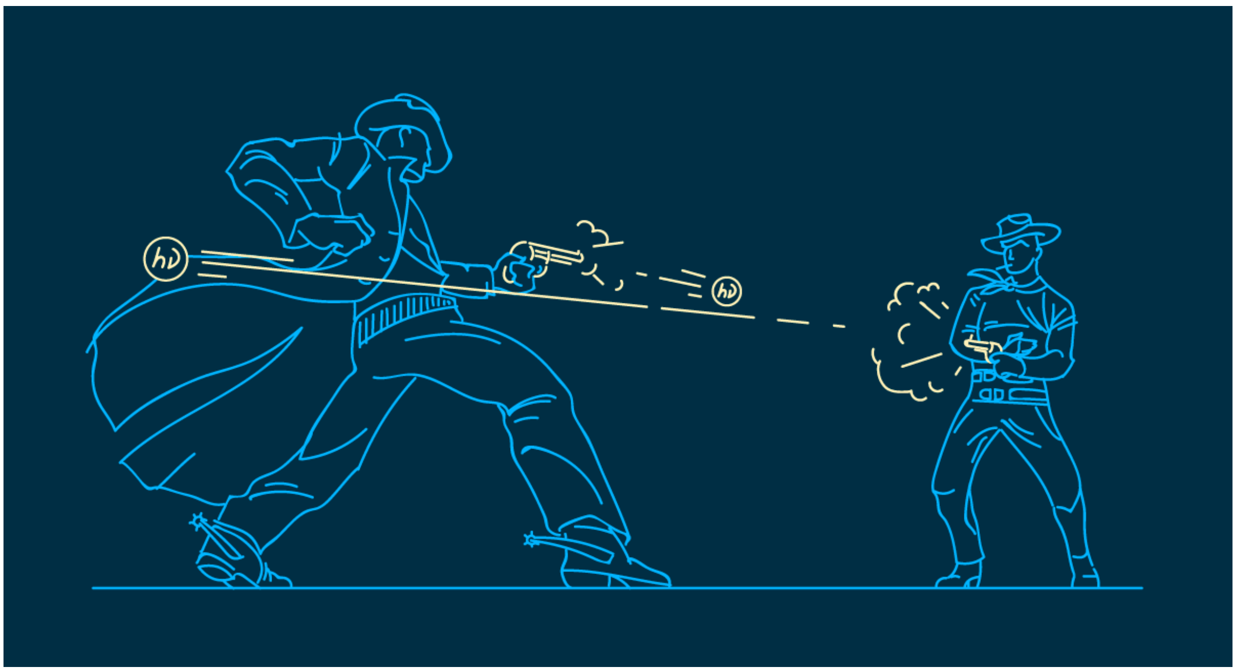

Credit: MIPT

Researchers from the Moscow Institute of Physics and Technology and the University of Siegen have explained the mechanism of single-photon generation in diamond diodes. Their findings, published in *Physical Review Applied*, offer new avenues for the development of high-speed single-photon sources for quantum communication networks and quantum computers of the future.

Operation at the single-photon level raises the possibility of developing entirely new communication and computing devices, ranging from hardware random number generators to quantum computers. Perhaps the most highly anticipated quantum technology is quantum communication. Quantum cryptography, which is based on the laws of quantum physics, guarantees unconditional communication security. In other words, it is fundamentally impossible to intercept the transmitted message, no matter the equipment or amount of computing power available to the hacker. Even a powerful quantum computer cannot help in this case. However, the implementation of quantum communication lines and other quantum devices inevitably relies on efficient single-photon sources.

It is a practical necessity that single-photon sources operate under standard conditions and be electrically pumped, that is, they should work at room temperature and be powered by a battery. These crucial requirements are not that easy to meet. First, quantum systems are not really compatible with high temperatures, which means they must operate in a refrigerator or cryostat in order to cool them to the temperature of liquid helium or even colder, to below 1 kelvin, which is equal to -272 degrees Celsius. Although the use of such devices has become standard practice in physical research, a cooling system of this kind is wildly impractical, inhibiting mass production of quantum devices. Also, the notion of a quantum system implies the absence of uncontrolled interactions with the surrounding environment. A classic example of such a system is a single atom in a vacuum chamber. Though its interaction with the environment is negligible, physicists can nevertheless control its electron states with a laser. By illuminating the chamber with a laser beam, an electron is promoted from an occupied lower-energy orbital to an empty higher-energy orbital. After that, the atom relaxes to the initial state via photon emission. The problem is that such a system cannot be electrically pumped.

Over the past two decades, ongoing research in the field of quantum optics and electronics has shown that even semiconductor quantum systems do not produce satisfactory results under electrical pumping at room temperature, whereas many of the other materials do not conduct electricity at all.

The surprising solution to this problem was previously found in diamond, a material that exhibits properties at the interface between semiconductors and dielectrics. Researchers found that certain points in the crystal lattice of diamond can function as quantum systems with outstanding photon emission characteristics. Moreover, they found that these quantum systems are capable of emitting single photons when an electric current is passed through diamond. Nevertheless, the physics behind this phenomenon remained unknown and it was unclear how to design fast and efficient single-photon sources based on color centers.

In the new paper, the researchers from MIPT and the University of Siegen established a mechanism of single-photon emission from electrically pumped nitrogen-vacancy centers in diamond and determined the factors affecting photon emission dynamics. According to their research, the single-photon emission process can be divided into three stages: (1) the electron capture by a color center, (2) the hole capture, meaning the loss of an electron, and (3) the electron or hole transitions between energy levels of the color center. Together, these three stages are analogous to a firing revolver.

Shooting a bullet in this analogy means emitting a single photon. An electron is captured by the defect—think of this as pulling back the hammer of a gun. Then the trigger is pulled, which sets the triggering mechanism in motion, throwing the hammer against the primer of the cartridge. This reversed motion of the hammer corresponds to the capture of a hole by the color center. Then the primer explodes, igniting the propellant, and the combustion gases drive the bullet along and out of the barrel. Similarly, the captured hole in the color center undergoes transitions between ground and excited states, which results in the emission of a photon. Subsequent cycles repeat the first cycle, with the exception that there is no need for a new cartridge, because the color center is capable of emitting any number of photons one at a time.

An important requirement for a practical single-photon source is that it has to emit photons at predetermined times, since the moment the photon is emitted, it flies away at the speed of light. "In a way, it's like a fast-draw duel in the Wild West," says Dmitry Fedyanin. "Two cowboys draw their guns the moment the clock strikes. Whoever shoots first is usually the winner. Any delay might cost each one of them his life. With quantum devices, the story is pretty much the same: It is crucial to generate a photon at precisely the time we need it." In their paper, the researchers show what determines the response time of a single-photon source, that is, the delay before the source emits a photon. They also evaluated the probability of emitting a new photon at time τ after the emission of the first photon. As it turns out, the response time can be adjusted and improved several orders of magnitude by changing the characteristics of diamond via doping or controlling the densities of electrons and holes injected into diamond. Apart from this, Fedyanin says, the initial state of the color center can be controlled by varying its position in the diamond diode. This is similar to how a gunslinger might cock the revolver for a faster shot or put the gun on half cock.

The physical model advanced by the researchers sheds light on the behavior of color centers in diamond. In addition to providing a qualitative interpretation, the proposed theoretical approach reproduces recent experimental results. This opens up a new possibility for the design and development of practical single-photon sources with desired characteristics, which are vital for the realization of quantum information devices, such as unconditionally secure communication lines based on quantum cryptography.

More information: Igor A. Khramtsov et al, Dynamics of Single-Photon Emission from Electrically Pumped Color Centers, *Physical Review Applied* (2017). DOI: 10.1103/PhysRevApplied.8.024031

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