Superinjection in single-photon emitting diamond diodes

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***Abstract*—Practical applications exploiting the quantum nature of light require efficient and bright room-temperature single-photon sources. At present, color centers in diamond are considered to be the most promising candidates. However, their efficient electrical excitation is challenging due to the inability to create a high density of free electrons in diamond. In this work, we predict the superinjection effect in diamond homojunction p-i-n diodes, which enables to inject up to four orders of magnitude more electrons into the i-region than the doping of the n-type region allows. Despite that the superinjection effect is known to be a unique feature of semiconductor heterostructures, we demonstrate for the first time that this effect can also be observed in homojunction diamond diodes, giving the possibility to overcome the doping problem and design bright electrically driven single-photon sources.**

Keywords— Single-photon emitting diode, color centers in diamond, superinjection in homojunctions.

I. Introduction

Despite the rapid development of quantum technologies, the absence of efficient bright true single-photon sources (SPSs) operating at room temperature hinders the development and implementation of many prospective quantum devices ranging from secure communication lines based on quantum cryptography to quantum computers. At present, color centers in diamond are considered as the most prospective platform for practical SPSs [1]. Their outstanding optical properties at room temperature combined with the possibility to trigger color centers electrically on demand [2,3] are what is required for building practical quantum information devices. Although the photoluminescence of color centers in diamond was extensively studied, the possibility of the design of an electrically driven SPS was not apparent until very recently, since diamond is a material at the interface between insulators and semiconductors. It cannot be as efficiently doped with donors as silicon or gallium arsenide. The activation energy of phosphorus (0.6 eV [4]), which is known to be the best donor-type impurity for diamond, is one order of magnitude higher than the activation energy of donors in silicon. Thus, at room temperature, it is almost impossible to create more than ~ 10^{11} cm^{-3} of free electrons in diamond [4,5]. At the same time, the recently developed theory of color center electroluminescence shows that the electroluminescence brightness is determined by the electron and hole capture processes [6–9]. Low carrier densities in the vicinity of the color center lead to low rates of carrier captures by the color center and consequently to low single-photon electroluminescence (SPEL) rates. Since in homojunction p-i-n diodes, the maximum density of free electrons in the i-region is typically limited by the electron density in the n-type injection layer [10], simple estimations show that due to the inability to create a high density of free electrons in diamond, the SPEL rate cannot exceed $c_n n_{eqn} \approx 1000$ cps, where n_{eqn} is the density of free electrons in the n-type injection layer of the single-photon emitting diode and c_n is the electron capture rate constant by the color center [9].

Here, using a rigorous numerical approach, we predict for the first time the superinjection effect [11,12] in diamond p-i-n diodes, which was considered to be unreachable in homojunction diode structures. We show that under superinjection conditions, it is possible to create a high density of free electrons in the i-region, which is more than three orders of magnitude higher than the electron density in the n-type injection layer of the diode. The predicted superinjection effect enables to overcome the doping difficulties in diamond and increase the maximum brightness of the diamond electrical SPS from about 1 kcps to 1900 kcps at room temperature.

II. Results

Figure 1 shows a schematic illustration of the diamond single-photon emitting diodes. The concentrations of donors in the n-type layer and acceptors in the p-type layer equal 10^{18} cm^{-3}. The donor compensation ratio is 10%, while the acceptor compensation ratio is as low as 1%, which is typical for diamond devices. The values of the electron and hole mobilities are calculated considering different scattering mechanisms and can be found in Ref. [5]. The thicknesses of p-, i- and n-type layers are equal to 5, 3 and 1 µm, respectively.

Under forward bias, electrons and holes injected from the n-type and p-type regions, respectively, recombine at the color center, which results in the single-photon emission [9].

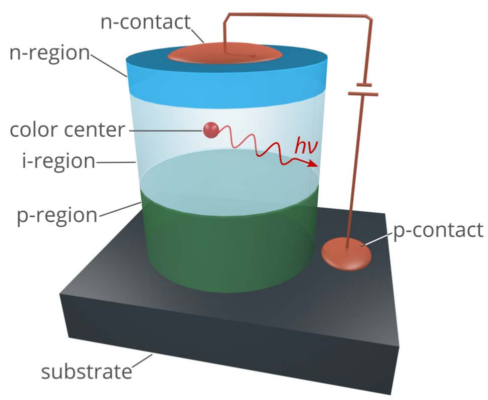

Fig. 1. Schematic illustration of the diamond p-i-n diode with a color center embedded in the i-region.

Due to the high activation energies of donors (0.6 eV) and acceptors (0.36 eV), the device cannot be described analytically. Therefore, we numerically simulate the electron and hole transport using the self-consistent model based on the Poisson equation, drift-diffusion current equations, and the electron and hole continuity equations. For more details on the numerical simulations, see Refs. [6,9]. The SPEL rate is calculated using the developed theoretical framework [6–9].

Figure 2 shows the simulated SPEL rate, which increases as the current increases but saturates at $J \approx 0.1$ mA/cm^2. For J in the range from 0.1 mA/cm^2 to 100 mA/cm^2, the maximum SPEL rate roughly a constant. It is achieved at i-n junction and is limited by the density of electrons n_{eqn} in the n-type layer. However, the SPEL rate starts to increase with the current at $J \approx 100$ mA/cm^2. It is clearly seen that as the current further increases, the optimum position of the color center shifts towards the p-i junction, while the SPEL rate in the optimum position steadily increases. The maximum SPEL rate is found to be as high as 1.9 Mcps, which is 3500 times higher than that at $J = 1$ mA/cm^2. Figure 3 shows the simulated energy band diagrams, which explains the observed unexpected increase of the SPEL rate above the doping limited value. At $V \approx 4.53$ V, a hardly recognizable potential well for electrons is formed in the i-region. The depth of the potential well increases as the bias voltage increases and the bottom of the well is shifted towards the p-type injection layer. Free electrons are accumulated in this potential well, which gives rise to the SPEL rate of the color center placed in this well. The physics of formation of the potential well is discussed in Ref. [5]. At very high voltages ($V > 6$ V), the potential well disappears as the bias increases, since the device completely switches from the diode regime to the resistor regime. This limits the maximum SPEL rate that can be achieved using the superinjection effect (Fig. 2).

III. Discussion

We have numerically demonstrated the superinjection effect in the diamond homojunction p-i-n diode, i.e., we have shown that under high forward bias, the density of electron in the i-region can be nearly four orders of magnitude higher than in the n-type injection layer, which is remarkable for homojunction diodes. Until recently, the superinjection effect, which is at heart of double-heterostructure lasers, was known to be a unique feature of semiconductor heterostructures [11,12]. It was not previously observed neither experimentally nor numerically in semiconductor homojunctions. We have for the first time shown that it is possible to reach the superinjection conditions in diamond homojunctions. At the same time, our study confirms that the superinjection conditions can hardly by achieved in homojunction p-i-n diodes based on conventional semiconductors. We have shown that the predicted effect can be exploited to increase the brightness of electrically driven diamond SPSs by more than three orders of magnitude, which opens new perspectives in the development of high-performance optoelectronic devices based on diamond and related wide-bandgap semiconductors.

Acknowledgment

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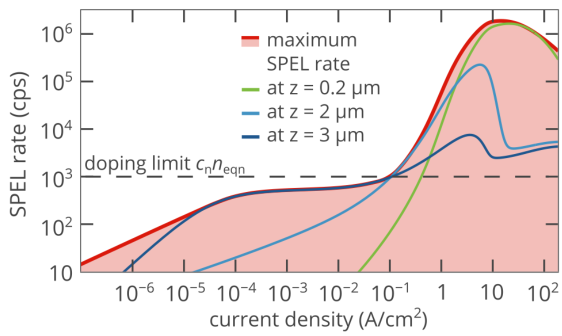

Fig. 2. Single-photon electroluminescence (SPEL) rate for three different positions of the color center in the p-i-n diode, z is the distance from the p-i junction. The red line shows the maximum SPEL rate that can be achieved in the considered diode. The quantum efficiency is assumed to be equal to 100%.

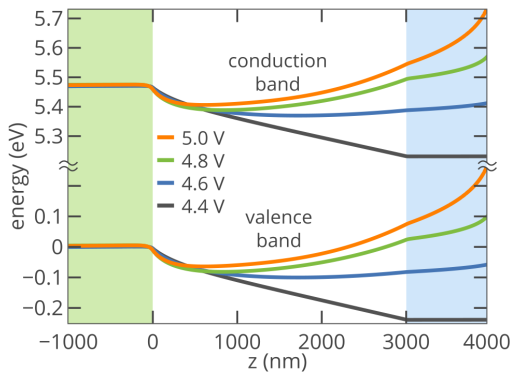

Fig. 3. Simulated energy band diagrams.

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