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Charge collection narrowing mechanism in electronic-grade-diamond photodetectors

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Recently, an extreme narrowband spectral response of only 8 nm in electronic-grade diamond-based photodetectors has been observed by Zheng Wei and his colleagues from Sun Yat-sen University for the first time. A charge collection narrowing mechanism assisted by free exciton radiative recombination is proposed, which well reveals the characteristic spectral response of diamond.

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As a wide-bandgap semiconductor, diamond possesses excellent physical and chemical properties, which is an ideal material for deep ultraviolet (DUV) photodetection[1,2]. For diamond, increasing the thickness of samples as a common method for narrowing charge collection[3,4] is not applicable because most photodetectors based on thick diamond single crystals will exhibit broad spectral responses due to the high mobility of diamond and carrier trapping effects[5]. Therefore, carrier lifetime, as another crucial parameter for adjusting spectral response, is essential for achieving narrowband photodetection[6,7]. A detailed analysis of the photonic characteristics of diamond is crucial for realizing the optical manipulation.

In a recent work[8] studied by Prof. Zheng Wei and his colleagues, the three different diamond single crystals studied in this report were named Diamond A, B, and C, with their dislocation densities increasing in sequence. Interestingly, the devices based on these single crystals exhibited markedly different shapes in their external quantum efficiency (EQE) spectra, with each full width at half maximum (FWHM) value of 8 nm, 31 nm, and 52 nm, respectively. The device based on Diamond A with low dislocation density showed an extreme narrowband response in the EQE spectrum and centered at 228 nm approximately. Simultaneously, it also displayed extremely low dark currents, high detectivity (~10^{13} Jones), and large linear dynamic ranges (LDR ~118 dB).

Figure 1(a) illustrates the main physical processes that may occur during the photo-detection of diamond, including photon excitation, carrier relaxation, radiation recombination, defect recombination, and photo-conduction under electric fields[9–12]. Diamond A shows extremely strong free exciton emission in the PL spectrum under 193 nm pulse excitation, based on which exciton emission can be determined as the primary recombination process under photon-excitation[13,14]. The spatial distribution of the generation rate of excess carriers in diamond under photon excitation follows Beer-Lambert's law. So through simplified calculations, the spatial distribution of charge carriers in the crystal under the excitation with different wavelengths can be obtained. As the excitation wavelength decreases, the carrier concentration in the crystal gradually decreases, with the maximum concentration moving toward the surface. In

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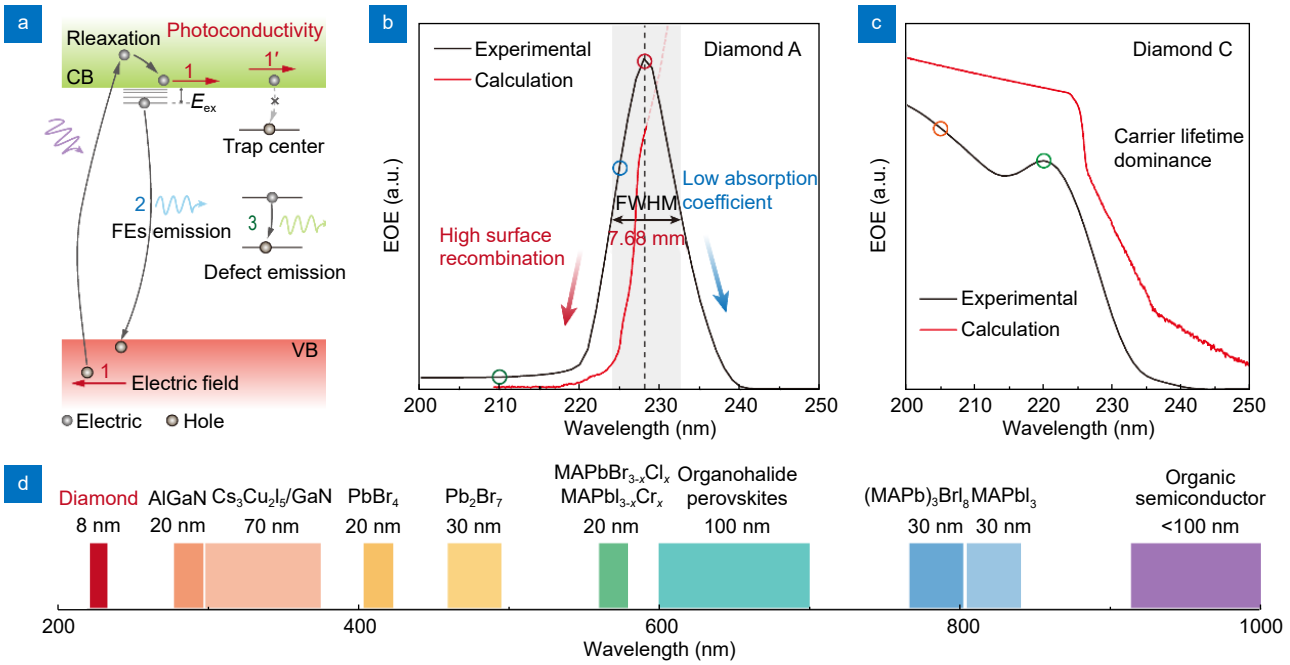

Fig. 1 | (**a**) Schematic of the main physical processes that may occur in diamond under photo-excitation. (**b**) EQE of the Diamond A-based photodetector from the experiment and calculation. (**c**) EQE of the Diamond C-based photodetector from the experiment and calculation. (**d**) Typical narrowband photodetectors in the spectral range of 200–1000 nm.

addition, strong absorption at the surface can lead to stronger radiative recombination, thereby significantly increasing the surface recombination velocity[15]. Consequently, the expression for the photo-conductivity equation of the device can be derived. As shown in Fig. 1(b), the black line represents the measured EQE of the device, while the red line represents the EQE calculated through the derived formula. In the low absorption coefficient region, photo-generated carriers can be excited throughout the crystal and collected by electrodes under the action of an electric field. As the excitation wavelength decreases, the increasing absorption coefficient brings a stronger response, which is a well-known mechanism in photodetectors[16,17]. After crossing the peak response, the photo-generated carriers gradually concentrate near the crystal surface. These carriers mainly undergo radiative recombination processes instead of reaching the back electrode, resulting in a significant decrease in response. For Diamond C, a higher trap state density results in a wider spectral response. According to its PL spectrum and transient excitation voltage response, photo-generated carriers contribute more to the photo-conductive process rather than the radiative recombination. The calculated EQE presented by the red line in Fig. 3(c) exhibits a trend consistent with that of the EQE measured experimentally. The higher dislocation density of Diamond C leads to more trap states in the crystal, and carriers will have a longer lifetime after being captured by those traps[18]. In the high absorption coefficient region, benefiting from the longer lifetime, carriers can be collected by the back electrode under the action of the electric field, thus avoiding the decrease in response.

In summary, the Diamond A-based photodetector reported in this work possesses the shortest detection wavelength and the narrowest EQE peak up to date (Fig. 1(d)), whose application potentials have been proved by the preliminary imaging demonstrations. Also, the narrowband response which can distinguish Diamond A from other ones illustrates that spectral response testing is a novel method for identifying electron-grade diamond. This work has been reported as a cover article in *Opto-Electronic Science* and is of great significance in revealing the photoelectric properties of diamond profoundly.

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