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Multi-color light-emitting transistors composed of organic single crystals

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ABSTRACT

We report a novel concept for multi-color light emission from an ambipolar organic single-crystal transistor using natural optical waveguides, the self-absorption effect, Davydov splitting and the unique alignment of the transition dipole moments. We used 9,10-bis-(2,2-diphenylvinyl)-anthracene single crystals to produce blue and green light from identical single-crystal transistors. We also observed red light, which corresponds to the emission from in-gap states that are caused by impurities. Importantly, each of these different colors corresponds to a distinguishable light polarization, which enables us to tune the emission color by using a light polarizer.

1. Introduction

The implementation of organic semiconductor-based devices, such as organic light-emitting diodes (OLEDs), organic solar cells, organic memories and organic field-effect transistors (OFETs), are predicted to reduce fabrication costs and enable plastic electronics [1–3]. Recently, a novel class of organic multi-functional devices was demonstrated and are termed organic light-emitting field-effect transistors (OLETs) [4–6]. The discovery of OLETs represents a very promising step in the development of highly integrated organic optoelectronic devices because these devices embody the smallest possible integration of a light source (OLED) and a switching device (OFET). Bright and multi-color OLETs may allow the fabrication of electroluminescent displays with simpler driving circuits [7–12]. With this discovery, the scope of future applications has been extended to include other optoelectronic device possibilities, such as electrical photomodulators and electrically driven organic lasers [13–16].

Among the various types of OLETs, single-crystal transistors exhibit high carrier-transport performance and unique optical properties [13–21]. The reported carrier mobilities of single-crystal OLETs are one to two orders of magnitude higher than those of thin-film OLETs. Notable optical functionalities in organic single crystals that were previously reported are the effects of optical confinement and self-waveguiding [15,16,18,21–23]. This light confinement is due to the perfect alignment of the molecules and the transition dipole moments, which is a specific feature of single crystals that causes the emitted light to be spontaneously polarized. Davydov splitting is another well-known polarizing feature of organic crystals, which leads to multi-color light emission [24–27]. Despite these interesting transport and optical advantages, the number of reported single-crystal ambipolar OLETs remains limited, and few studies have been published on the effective utilization of such unique optical properties. Here, we introduce the novel concept of multi-color OLETs using

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natural optical waveguides, the self-absorption effect, Davydov splitting and the unique alignment of the transition dipole moments. The confined light inside very thin single-crystal waveguides changes color due to the self-absorption effect, and we were able to tune the emitted color from blue to green using this unique effect. We also observed polarized red emission from organic crystal impurities and were able to produce red/green/blue emission from an individual OLET. The effects of the polarizability due to the dipole alignment and Davydov splitting enabled us to perform color selection from an individual OLET using a light polarizer.

2. Method

2.1. Design principles of the multi-color OLETs

Fig. 1a illustrates our strategy for the fabrication of multi-color LETs. In most organic molecules, the material photoluminescence (PL) spectrum exhibits an overlap with the absorption spectra. Due to this spectral overlap, the emission color strongly depends on the length of the light path inside the organic material. A longer light path leads to stronger self-absorption, hence the color of emitted light becomes red-shifted. We used a very thin single-crystal waveguide to apply this self-absorption effect for color tuning because the optical path of emission from the crystal surface is much shorter than that of the waveguided edge emission in a very thin single crystal (Fig. 1a).

However, to emit light from the surface and the edge, the relative direction of the molecular transition dipole moment to the crystal surface is crucially important. In very thin single crystals of thiophene/phenylene co-oligomers, the PL emission is naturally confined within the crystals, and only the crystal fringes are luminescent [15,16,18,21–23]. This unique emission is due to the standing alignment (i.e., parallel to the normal of the crystal surface) of the transition dipole moments inside the crystals. In stark contrast, tetracene single crystals exhibit obvious surface emission, which can be explained by the lying alignment (i.e., perpendicular to the normal of the crystal surface) of the dipoles [17]. For our novel concept, we require inclined transition dipole moments with respect to the normal of the crystal surface. As shown in Fig. 1a, for this unique alignment of the transition dipole moments, the mirrored crystal surface splits the emitted light into short-optical-path surface emission and waveguided long-optical-path edge emission. Based on this strategy, we selected a material that exhibited the self-absorption effect and fabricated LETs using very thin single crystals of the same material that also exhibited a tilted alignment of the transition dipole moments.

2.2. Material

The material of choice was 9,10-bis-(2,2-diphenylvinyl)-anthracene (DPVA, the inset of Fig. 1b). Although DPVA is commercially available (ADS085BE, American Dye Source, Inc.), the optical properties of this material have not been reported [28].

2.3. Photoluminescence and absorption measurement of the DPVA thin films

We fabricated spin-coated DPVA films from a chloroform solution onto quartz substrates and investigated their

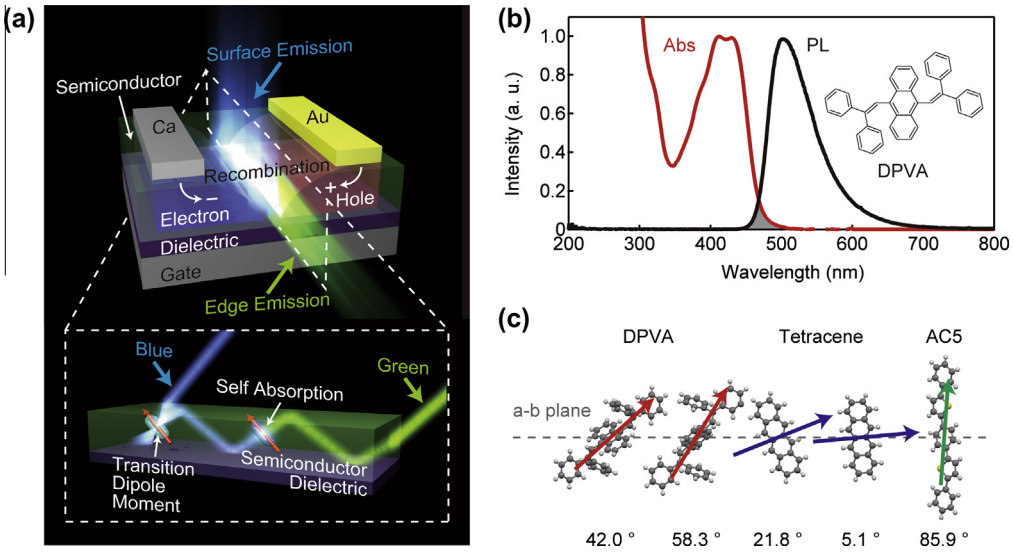

Fig. 1. (a) A conceptual representation of the novel color tuning with a very thin organic single crystal. (b) The PL and absorption spectra of the DPVA thin film. The inset shows the chemical structure of a DPVA molecule. The gray area shows the overlap between the PL and absorption spectra. The absorption edge appears at approximately 510 nm. (c) The relationship between the molecular orientation and the crystal surface in DPVA, tetracene and 1,4-bis(5-phenylthiophen-2-yl)benzene (AC5) single crystals. The *ab* plane is parallel to surface of the thin crystal. The red, blue and green arrows indicate the calculated directions of the transition dipole moments in DPVA, tetracene and AC5 molecules, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)