Visualization of invisible near-infrared light

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In the era of digital and information technology, near-infrared (NIR) light sensing exhibits significant potential in expanding the scope of human vision and machine intelligence, by involving in ubiquitous applications in the fields of security monitoring, medical diagnosis, military combat, and industrial inspection. Conventional NIR imagers integrate inorganic detector arrays with readout integrated circuits (ROICs) and require sophisticated image processing algorithms to display the NIR target, where strict lattice matching and back bonding are required thus imposing limitations in pixel size and cost. In

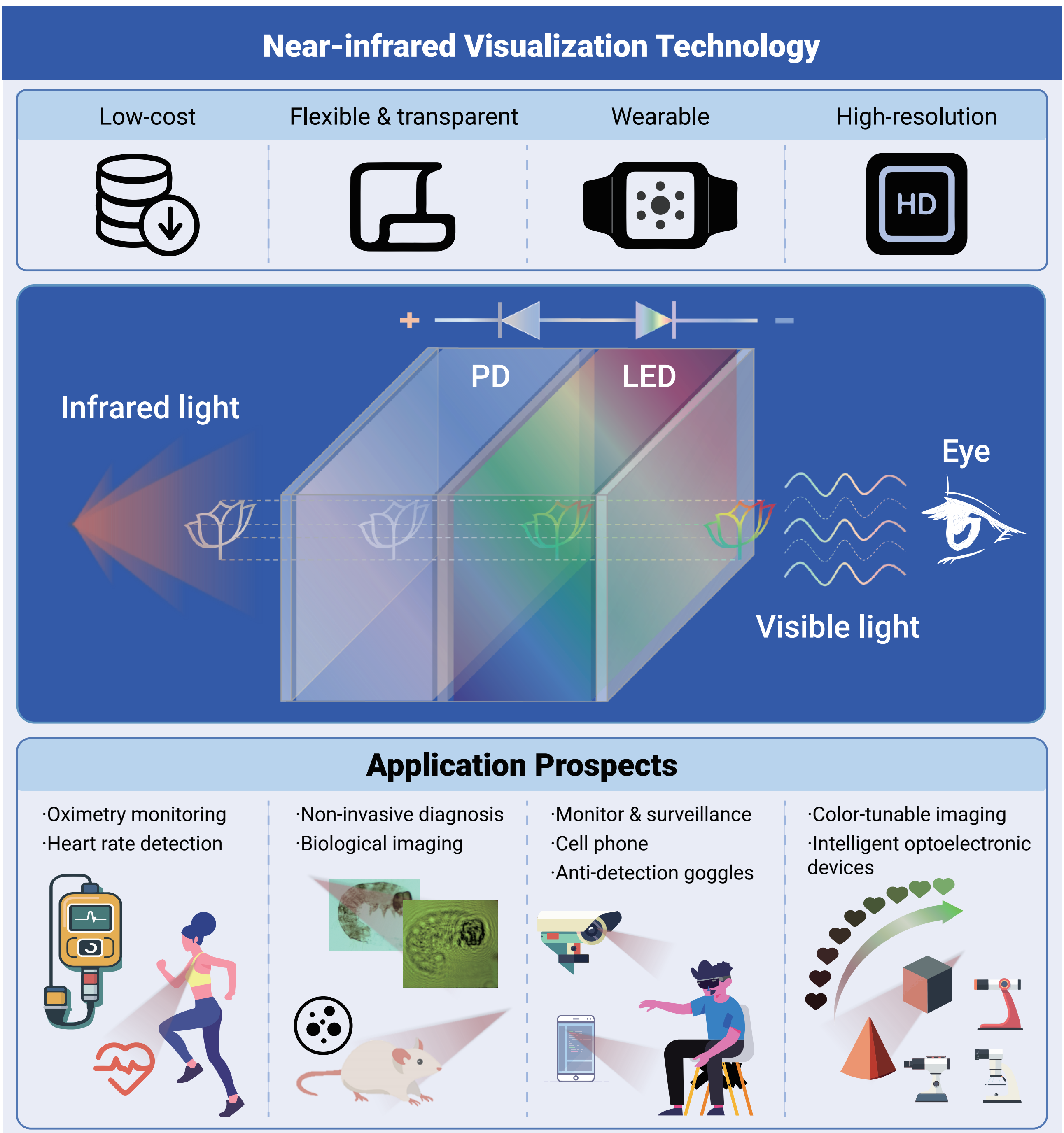

Figure 1. Schematic diagram of NIR visualization technology enabled by a upconversion device and its future application prospects The PD and LED in figure are photodetector and light-emitting diode, respectively.

contrast, NIR-to-visible upconversion devices (UCDs) can directly convert infrared signals into visible light by integrating an infrared sensing unit and a visible light-emitting unit (Figure 1), providing a feasible and cost-effective way for direct visualization of invisible NIR light. This emerging NIR-to-visible UCD is a pixel-less imaging technique, which avoids the use of high-density ROICs and possesses the advantages of solution processability, low cost, flexibility, and biocompatibility. It has attracted considerable attention in recent years.

Despite the advantages of the UCDs for NIR visualization, the current technology still faces drastic challenges in upconversion efficiency ($\eta_{\text{p-p}}$), detection sensitivity, and imaging resolution. Thus, there are still issues to be resolved to promote the commercialization of such technology. The $\eta_{\text{p-p}}$ and detection sensitivity are considered the primary challenges in UCDs, which mainly stems from the mismatch between the optical and electronic properties of the detection and light-emitting units. In addition, the quality of the film morphology, energy level matching between functional layers, and charge transfer capability of the materials are also crucial factors in affecting the $\eta_{\text{p-p}}$ and detection sensitivity of the UCD. The key factors that determine the imaging resolution of the UCDs concentrate on the carrier lateral migration which highly depends on the charge carrier mobility and trap distribution of the films.

Recently, Tao et al. constructed a high-efficiency and low-energy consuming all-organic UCD by combining the solution process and thermal evaporation.[1] Ternary hybrid heterojunctions are first introduced to prepare the NIR photosensitive layer, which effectively enhances the photon-induced exciton generation and dissociation in the device. As a result, a low turn-on voltage of 1.56 V and a high $\eta_{\text{p-p}}$ (from 895 to 524 nm) of up to 12.92% were realized in the UCD. The low-bias and highly efficient UCD was utilized for bio-imaging, showing excellent image quality with better recognition of the internal structure of living organisms as compared to charge-coupled device photographs. This work presents a strategy to improve the efficiency of UCDs, paving the way to pixel-free, high-resolution, and non-toxic imaging technique for non-invasive imaging and biomonitoring applications.

The detection sensitivity in an UCD is of great importance for practical uses. In a recent study published in *Science Advances*, Liu et al. proposed an antidetection panel based on a high-sensitivity, high-resolution, and transparent organic UCD.[2] The detection limit of this UCD is as low as 0.75 $\mu W/cm^2$ and the maximum $\eta_{\text{p-p}}$ (from 940 to 523 nm) reaches 12.56% at power density of 103.8 $\mu W/cm^2$, due to the elaborately controlled device structure and film quality. The dramatically improved sensitivity enables the detection of NIR signals in real-time environment, including hidden cameras, monitors, and sneak shots. This work provides an important insight into the prompt monitoring of invisible infrared signals in daily life and accelerates the commercial development of upconversion imaging technology.

NIR UCDs based on organic materials have shown unprecedented performances and hold the great potential for practical applications. However, the optical absorption edges of most organic materials are usually limited within 1100 nm, which is highly overlapped with silicon-based devices. Further expanding the sensitive wavelength range of UCDs is essential to fit various application requirements. The recent rapid developments in infrared colloidal quantum dot (QD) semiconductors made it possible to extend the detector sensitivity to longer wavelengths, e.g., shortwave infrared or even mid-wave infrared. The solution processability of QD materials is comparable with organic semiconductors to make detectors flexible and low-cost. More encouragingly, all QD based UCDs are possible, because QDs can be used as light emission layers in UCDs with much narrow emission spectrum, as well as photosensitive layer in the UCDs with tunable response spectrum by adjusting the QD size. Ning et al. demonstrated a high-performance UCD based on colloidal QDs, fabricated via a solution process.[3] The PbS QDs and CdSe/ZnS QDs were employed as the NIR photosensitive layer and visible emission layer, respectively. A direct visualization of NIR light up to 1500 nm was achieved. The maximum $\eta_{\text{p-p}}$ (from 940 to 525 nm) reaches 6.5%, comparable to the value reported for InGaAs photodetectors.[3] The photomultiplication process in the PbS QD based detection unit dramatically improves the $\eta_{\text{p-p}}$ results. As a result, the clear imaging of the mouse breast cancer tissue sections under NIR wavelengths was successfully demonstrated, indicating the feasibility of the QD-based UCD for biomedical diagnosis. However, it should be noted that the penetration of solutions in all-solution processed UCDs may cause erosion to the underlying layer upon fabricating the top layer. To deal with this problem, the choice of orthogonal solvents for the semiconductors needs to be carefully considered. In addition, the reabsorption and blocking of emitted visible photons by the NIR sensitive QDs layer deteriorate the upconversion efficiency. A delicate design in the device structure, such as incorporating optical structures to facilitate the visible light out-coupling or adopting a top-emission structure, is critical.

In terms of the visible signal from the UCDs, almost all UCDs are developed to emit monochromatic light that depends on the emissive layer of the LED unit. The intensity of the incident NIR signal is generally reflected only through the brightness of the visible light. Given that human eyes are also sensitive to the variations in color, it would be more favorable to correlate the invisible NIR signal intensity to different visible colors in the UCDs. Furthermore, the color-tunable UCDs with multi-signal are easily integrated into intelligent optoelectronic devices, possessing great application prospects in interactive displays, smarting lighting, and electronic skin sensors. Tang et al. recently proposed a silicon/color-tunable organic light-emitting diode (Si/CTOLED) device structure in which the infrared intensity can influence the visualization colors, enabling pseudo-color imaging of infrared light.[4] Very recently, Lei's group proposed a quite different strategy for colorful visualization of NIR light.[5] They mixed the red and green QDs in a single emissive layer for multi-color emission in solution-processed UCDs, successfully building a qualitative correlation between incident NIR intensity and visible emission color. These two studies are inspiring and provide insights into the development of colorful interactive displays for NIR sensing, which may find applications in multi-disciplinary fields.

In conclusion, NIR visualization enabled by the UCDs provides a new way to develop portable and wearable NIR sensing devices. The advantages in material choice, structure design and function control of the UCDs are of great significance for versatile application requirements. Besides organic materials and quantum dots, perovskites and two-dimensional materials can also be used to construct efficient UCDs. Given that high-performance NIR light sensing is under urgent needs, the developments in new strategies for NIR visualization that enables large area, high resolution and ease of fabrication, are essential steps for the future detection technology. Up to now, upconversion efficiency and detection sensitivity, as the core performance indexes of UCDs, are still the key directions to be broken through in the future development of UCDs. Especially the ability of weak light detection is very important for the scene applications of UCDs. We envision versatile NIR visualization and detection methods that will definitely benefit the future smart and highly miniaturized optoelectronic devices.

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DECLARATION OF INTERESTS

The authors declare no competing interests.