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Beyond visible: giant bulk photovoltaic effect for broadband neuromodulation

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Abstract

The giant bulk photovoltaic effect in tellurene nanomaterials has been harnessed to enable broadband infrared neuromodulation, expanding the potential for safe, non-invasive neural stimulation and highlighting the importance of material innovation in advancing infrared photonic applications.

Efficient conversion of light into electricity is crucial across a wide range of fields, from imaging and biological sensing to clean energy and free-space communication. The bulk photovoltaic effect (BPVE) has recently attracted attention for its remarkable ability to surpass the traditional efficiency limits of conventional solar cells, known as the Shockley-Queisser limit¹. Unlike typical solar cells, which rely on p-n junctions to generate electricity, BPVE operates in materials without a center of symmetry (non-centrosymmetric materials)², producing a photocurrent directly from light exposure without the need for a p-n junction. This unique mechanism offers exciting potential for more efficient light-to-electricity conversion in cutting-edge applications.

In the late 20th century, scientists began focusing on identifying materials suitable for the BPVE and understanding its underlying mechanisms, as illustrated in Fig. 1. Early studies revealed that certain materials, such as ferroelectrics like BaTiO₃ and LiNbO₃, along with specific organic compounds, showed promising BPVE properties³. These initial discoveries laid the groundwork for optimizing these materials to improve their performance. As material science advanced, researchers discovered new BPVE-active materials, including organic semiconductors and two-dimensional materials^{4,5}, which greatly expanded BPVE applications by achieving impressive efficiencies in the ultraviolet (UV) and visible (VIS) light ranges⁶.

Currently, however, BPVE responses are generally limited to a narrow range of wavelengths due to interband optical transitions in conventional semiconductors and heterostructures. While some phenomena (e.g., Berry curvature and scattering in semimetals) could potentially support BPVE generation in the infrared range, achieving photoelectric conversion with polarized single-wavelength light remains challenging⁷. This effect, related to the circular photogalvanic effect, highlights the need for further research into materials that can achieve a broadband BPVE response, especially in the infrared range, where detection remains challenging but holds immense potential for applications.

Recently, a collaborative research team led by Professor Weida Hu from the Shanghai Institute of Technical Physics, Chinese Academy of Sciences, achieved a major breakthrough in extending BPVE into the MIR range⁸. Building on their prior work with low-dimensional tellurene (Te) nanomaterials^{9,10}, the team synthesized Te nanomaterials using chemical vapor deposition, resulting in devices that exhibit a wide-ranging BPVE response—from UV to MIR wavelengths, covering ~0.39 to 3.8 μm. Using scanning photocurrent mapping, the researchers evaluated the infrared response of these materials, finding it to be consistently robust across the VIS to infrared spectrum and primarily localized within the channel itself. Remarkably, the Te materials demonstrated a high photocurrent density of ~70 A cm⁻² under infrared light, greatly surpassing the performance of other known BPVE materials.

Exploring potential applications, the team tested Te nanomaterials for broadband optical neuromodulation. When co-cultured with primary cortical neurons, the Te nanoflakes successfully triggered action potentials (electrical

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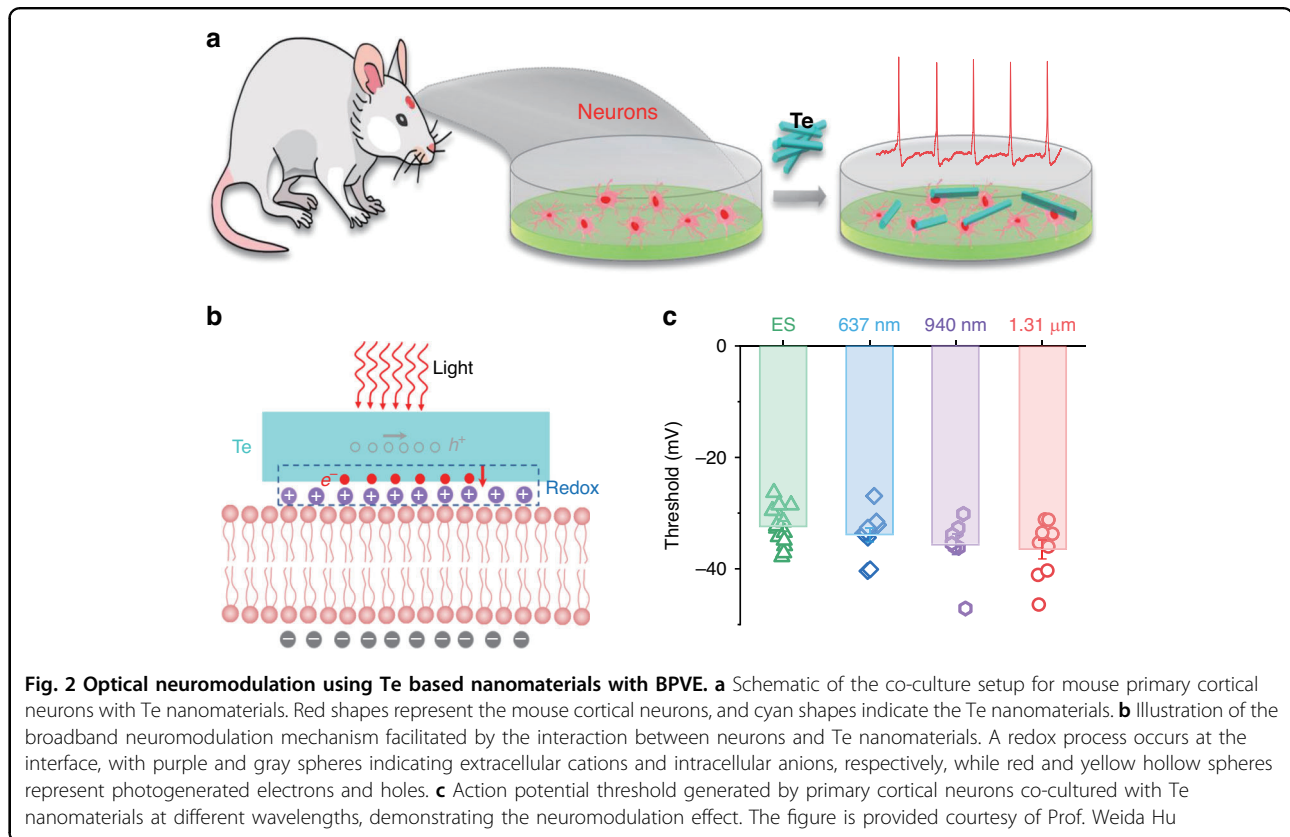
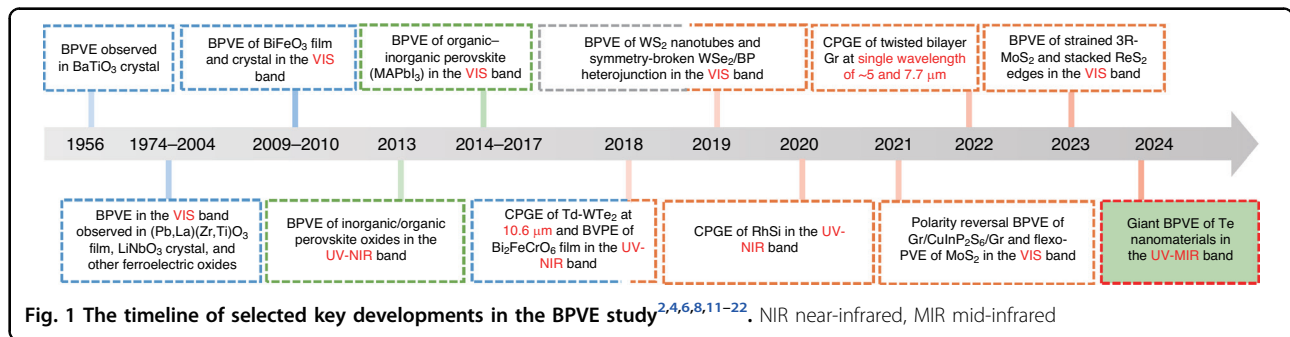
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impulses) in neurons when exposed to light at various wavelengths, including ~637, 940, 1310, and 1550 nm, as shown in Fig. 2. This effect was achieved without any extra external electrical stimulation, yet the action potentials produced were comparable to those seen with traditional electrical methods. The process occurs as photogenerated carriers from the BPVE diffuse into the extracellular medium, altering the transmembrane voltage and activating neuronal activity. Importantly, the Te nanoflakes showed no signs of cytotoxicity or cell damage, even after prolonged exposure, underscoring their biocompatibility and suitability for potential biomedical applications.

These findings highlight the strong potential of Te for broadband infrared applications, particularly in the field

of non-invasive neuromodulation, where it could offer safer, more versatile options for influencing neural activity. Further research into Te and similar nanomaterials is crucial, as advancements in this area could open new pathways for safer medical technologies and expand the possibilities of infrared applications across various fields, from biomedical engineering to advanced imaging.

Conflict of interest

The authors declare no competing interests.

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