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THE ROLE OF HALIDE PEROVSKITE MATERIALS IN THE DEVELOPMENT OF HIGH-EFFICIENCY SOLAR CELLS

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Abstract. This paper analyzes the physical properties of halide perovskite semiconductors and their potential for the development of high-efficiency, low-cost photovoltaic devices. Particular attention is paid to the crystal structure, optical absorption, charge-carrier transport, defect tolerance, and band-gap tunability of perovskite materials, as well as to the factors limiting the stability of perovskite solar cells and the prospects of perovskite/silicon tandem structures.

Keywords: solar energy, perovskite, semiconductor, band gap, photovoltaic effect, charge carriers, renewable energy.

Today, the growing demand for clean energy sources makes the development of efficient photovoltaic technologies one of the key tasks of applied physics. The operation of a solar cell is based on the photovoltaic effect: photons with energy exceeding the band gap of a semiconductor generate electron–hole pairs, which are then separated by the built-in electric field of a p–n junction or an equivalent junction structure [4]. The efficiency of a cell is determined by the ratio of the maximum output electrical power to the incident light power, $\eta = (V_{oc} \cdot J_{sc} \cdot FF) / P_{in}$, where V_{oc} is the open-circuit voltage, J_{sc} is the short-circuit current density, and FF is the fill factor. The theoretical efficiency of a single-junction solar cell is limited by fundamental losses, including thermalization of hot carriers and the non-absorption of photons with energy below the band gap; this restriction is known as the Shockley–Queisser limit and amounts to about 33% for a band gap of 1.3–1.4 eV [3].

Since the first demonstration of organometal halide perovskites as light sensitizers in photovoltaic cells [1], these materials have attracted considerable attention. They have the general formula ABX_3, where A is a monovalent cation (for example, methylammonium, formamidinium, or cesium), B is a divalent metal cation (usually Pb^{2+}), and X is a halide anion (I^-, Br^-, or Cl^-). Their high optical absorption coefficient, of the order of 10^4–10^5 cm^{-1} in the visible range, allows an absorber layer only a few hundred nanometers thick to capture most of the incident light [2]. Charge carriers in perovskite films also have long diffusion lengths, which in high-quality mixed-halide films exceed one micrometer [5], so that photogenerated electrons and holes can reach the contacts before they recombine. Another important advantage is the tunability of the band gap: partial substitution of iodine by bromine shifts the absorption edge toward shorter wavelengths and widens the band gap from about 1.5 eV to more than 2 eV [6]. Calculations show that the dominant point defects in these materials create mainly shallow energy levels near the band edges, which explains their relatively high tolerance to structural imperfections [7]. As a result, the power conversion efficiency of laboratory perovskite cells has increased from a few percent

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to more than 25% within little more than a decade, while the films can be produced by simple solution-based methods at low temperatures.

At the same time, the practical application of perovskite solar cells faces a number of physical and technological challenges. Degradation of the material under the influence of moisture, heat, and illumination, ion migration within the crystal lattice, and the presence of defect states that promote non-radiative recombination reduce the long-term operational stability of devices. Ion migration is also associated with the hysteresis of current–voltage characteristics, which complicates the accurate measurement of efficiency. In addition, the use of lead in the most efficient compositions raises environmental concerns, which stimulates the search for less toxic alternatives and for reliable encapsulation methods.

Combining perovskite layers with silicon in tandem structures is regarded as a promising approach to higher efficiency. In such a device, a wide-band-gap perovskite top cell absorbs the high-energy part of the solar spectrum, while a narrower-band-gap silicon bottom cell utilizes the remaining photons, thereby reducing thermalization losses and overcoming the efficiency limit of a single junction. Monolithic perovskite/silicon tandem cells with efficiencies above 29% have already been demonstrated [8]. Further progress depends on the improvement of interfaces between the layers, the suppression of phase segregation in wide-band-gap compositions, and the scaling up of fabrication from laboratory samples to large-area modules [2, 8].

Conclusion. Halide perovskites combine favorable optoelectronic properties — strong light absorption, long carrier diffusion lengths, tunable band gap, and defect tolerance — with simple and low-cost fabrication methods, making them one of the most promising materials for next-generation photovoltaics. However, wide commercial implementation requires further study of defect physics, ion migration, degradation mechanisms, and lead-free alternatives. Therefore, it is essential to deepen the fundamental understanding of charge-carrier processes in these materials, and to introduce the physics of perovskite semiconductors into the training of future specialists in renewable energy, in order to improve both the efficiency and the stability of solar cells.

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