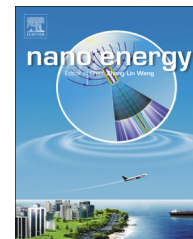




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RAPID COMMUNICATION

Harsh photovoltaics using InGaN/GaN multiple quantum well schemes



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Abstract

Harvesting solar energy at extremely harsh environments is of practical interest for building a self-powered harsh electronic system. However, working at high temperature and radiative environments adversely affects the performance of conventional solar cells. To improve the performance, GaN-based multiple quantum wells (MQWs) are introduced into the solar cells. The implementation of MQWs enables improved efficiency (+0.52%/K) and fill factor (+0.35%/K) with elevated temperature and shows excellent reliability under high-temperature operation. In addition, the GaN-based solar cell exhibits superior radiation robustness (lifetime > 30 years under solar storm proton irradiation) due to their strong atomic bonding and direct-bandgap characteristics. This solar cell employing MQW nanostructures provides valuable routes for future developments in self-powered harsh electronics.

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Introduction

Harsh electronics is an emerging field aiming at the promotion of device capability and applicability in harsh environments, including the extremes of pressure, vibration, and chemically corrosive environments [1,2]. For practical uses, harsh electronic systems are required to be self-powered and operated independently because their working environments are usually inaccessible for human [3–6]. In general cases, sunlight is one

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of the most suitable energy sources due to the absence of resources in harsh terrains. However, a harsh environment-sustainable solar cell is still deficient, because most semiconductor photovoltaic (PV) devices suffer serious degradation under high temperatures (volcanos, outer space, planet's orbits and near-sun missions) and long-term radiation exposure (cosmic rays, upper layers of the atmosphere, military and civil nuclear facilities) [7]. The performance loss in high-temperature environments is due to the narrowing of bandgap while elevating the temperature, which leads to a severe decrease of open-circuit voltage (V_{oc}) and fill factor (FF), resulting in an overall degradation of efficiency [8]. For example, the efficiencies of crystalline Si and GaAs solar cells are reduced by $\sim 0.45\%$ and $\sim 0.21\%$ for every degree increase at the temperatures higher 40°C , respectively [9]. In addition, under long-term radiation exposure, the high-energy particles deteriorate the performance of solar cells over time and eventually result in failure/reset. Although off-pointing technology, active cooling techniques, and passivation from radiation are possible approaches, a reliable PV operation in high temperature regimes with high radiation resistance is still demanded [10].

From the material point of view, wide bandgap compound materials are obvious choices for high-temperature device applications [11,12]. GaN, a wide- and direct-bandgap material, is a promising candidate for such applications with several favorable properties such as tunable bandgap through indium incorporation, high absorption coefficient, and high mobility [13,14]. GaN-based solar cells hold promises to reach a theoretical efficiency over 40%, and the incorporation of hierarchical structures has shown the potential to achieve the goal [15,16]. In addition, GaN-based materials exhibit a higher resistance to high-energy proton irradiation than the conventional III-V materials such as GaAs and GaInP [17]. The superior radiation resistance makes GaN a potential candidate for space applications.

Structure design is another approach to achieve the high efficiency. It is known that incorporating nanostructures and heterojunctions in solar cells can improve the efficiency due to the extension of absorption spectrum [18]. Multiplication of the junctions by forming multiple quantum wells (MQWs) can further optimize their bandgaps and reduce radiative losses, leading to a higher efficiency than those of single quantum well (SQW) or homogeneous p-i-n solar cells [19,20]. In addition, for solar cells used in space, the addition of quantum wells (QWs) also improves the radiation hardness [21,22].

In this study, we explore InGaN/GaN MQW high-temperature solar cells with superior radiation tolerance promising to harsh-environments/space applications for the first time. Different from conventional solar cells, short-circuit current (J_{sc}) and FF of MQW solar cells remarkably increase with temperature due to the implementation of GaN-based materials and MQWs, which results in a significant improvement in efficiency at 700 K. Moreover, the PV devices retain the initial performance at room temperature after high-temperature operation without failures or thermal breakdowns. Under high-energy proton irradiation, the devices exhibit a slow degradation compared to conventional solar cells, demonstrating a predicted lifetime of >30 years under solar proton storm. This study paves the way for InGaN/GaN MQW solar cells to harvest energy efficiently under extremely harsh (hot/radiative) environments.

Experimental section

Preparation of MQW solar cells

The device geometry of the InGaN/GaN MQW solar cell is illustrated in Fig. 1a. MQW solar cells were grown by metal-organic chemical vapor deposition on c-plane sapphire substrates. The QW is composed of $\text{In}_x\text{Ga}_{1-x}\text{N}$ with $x=0.15$ to minimize the indium fluctuation [14]. As shown in the high-angle annular dark field scanning transmission electron microscopy (STEM) images shown in Fig. 1b, 12 periods of InGaN/GaN MQWs are sandwiched between $2.5\text{-}\mu\text{m}$ n-type and 200-nm p-type GaN layers. Indium tin oxide (ITO) was deposited by electron beam evaporation on p-GaN to form transparent ohmic contacts, and $1 \times 1\text{ mm}^2$ diode mesas were defined by chlorine-based plasma etching. The electrodes were formed by depositing interdigitated metal (Ti/Al/Ni/Au) grids on the top surfaces of ITO and n-GaN.

Characteristics

To characterize the device performance, external quantum efficiency (EQE) and electroluminescence spectrum (EL) were performed, as shown Fig. 1c. The broadband absorption (350–450 nm) corresponds to a wide bandgap distribution of the MQWs, and the EL peak of 459 nm corresponds to blue light emission consisting with previous results of $\text{In}_{0.15}\text{Ga}_{0.85}\text{N}$ [23,24]. One can see that the peak wavelength for EL is longer than that of EQE, which accounts for the fact that in emission process the carriers relax to lower energy levels through

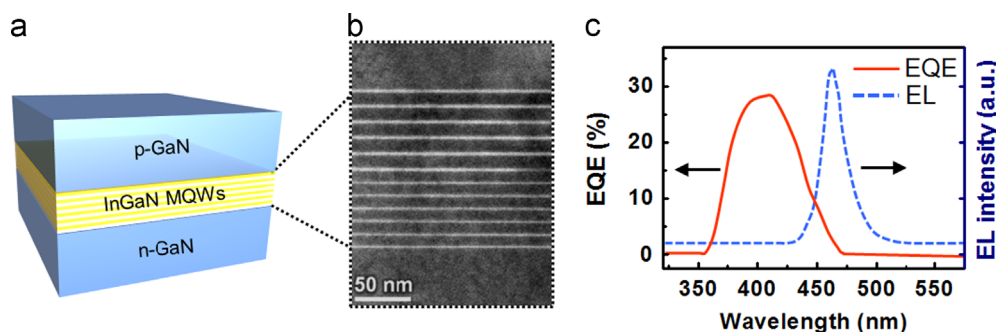


Fig. 1 (a) Schematic of the InGaN/GaN MQW solar cells. (b) High-angle annular dark field STEM images of the MQWs. (c) EQE and EL spectra of the InGaN/GaN MQW solar cells.

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