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# Effects of proton irradiation on upright metamorphic GaInP/GaInAs/Ge triple junction solar cells

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## ABSTRACT

The electrical parameters and external quantum efficiency (EQE) of 3 MeV and 8 MeV proton beam irradiated upright metamorphic (UMM) GaInP/GaInAs/Ge triple-junction solar cells, grown by metal-organic chemical vapor deposition, have been investigated and compared to lattice-matched (LM) GaInP/GaInAs/Ge solar cells. High-resolution X-ray diffraction was used to study the relaxation of strain by analysing reciprocal space maps. Threading dislocation density was estimated from cathodoluminescence image. SRIM simulation results have been applied for analysing the irradiation induced displacement damage and its effects on cell performance. The results show that the electrical parameters of both UMM and LM cells degraded more by 3 MeV proton compared to 8 MeV proton irradiation. The degradation of $V_{oc}$ and $I_{sc}$ depends on each other in both UMM and LM cells but have different features under proton irradiation due to different cell configurations, materials, and parameters etc. EQE spectra of UMM and LM cells mainly degrades in longer wavelength region due to the reduction of minority carrier diffusion length. Top GaInP subcell in UMM cell shows better radiation resistance than LM cell due to the higher In-P composition, and middle GaInAs middle subcell in UMM structure shows weaker radiation resistance because of the relatively higher indium composition.

## 1. Introduction

The photovoltaic conversion efficiency of the state-of-art lattice-matched (LM) $Ga_{.51}I_{n0.49}P/Ga_{.99}In_{.01}As/Ge$ triple junction solar cell is limited by the mismatch between the bandgaps combination and a given solar spectrum [1,2]. Meanwhile, higher efficiencies can be achieved with metamorphic (MM) structure by lowering the bandgap energies of top and middle subcells or replace Ge subcell with a 1.0 eV $Ga_{.7}In_{.3}As$ junction based on theoretical calculations [2,3]. However, the optimum bandgap combination is normally attained using materials with different lattice constants. Growing layers with different lattice constant will generate strain which causes the deformation of the lattice, and the strain can be relieved by introducing dislocations. The existence of dislocation, especially threading dislocation, can significantly decrease the performance of the multijunction solar cell by increasing nonradiative recombination in active layers. Therefore, traditional epitaxy process, where the layers are lattice-matched, are not suitable for MM configuration. Presently, there are two approaches, monolithic and non-monolithic, are adopted to combine materials with different lattice constants to achieve high conversion efficiency. In non-monolithic approaches, multiple substrates with different lattice constants are used to separately grow lattice-matched subcells, then the cells combined through wafer bonding [4] or mechanical stacking [5]. In monolithic approaches, a compositionally graded buffer (CGB) layer is introduced to relieve the strain in a controlled way. It can be divided into two categories, inverted metamorphic (IMM) [6,7] and upright metamorphic (UMM) [8,9], based on the fabrication methods. However, mechanical stacking, wafer bonding, and inverted metamorphic cells require complicated fabrication process and not cost-effective. On the other hand, the fabrication process of UMM cell is completely compatible to the state-of-art technologies of LM cell. Experimentally, R. R. King et al. demonstrated a conversion efficiency of 40.7% under high concentration for terrestrial application [10]. Furthermore, UMM cell has achieved efficiency over 31.0% under 1 sun AM0 spectrum, while the efficiency of traditional LM solar cells is limited to 30% [11]. These features make UMM multijunction solar cell a promising

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candidate for next-generation space solar cells.

Since the space solar cells are exposed directly to the harsh space environment, stable and reliable operation of solar cells is the guarantee of space mission. The effect of displacement damage caused by high-energy particles in space radiation environment plays a major role in the degradation of photovoltaic conversion efficiency of solar cells [12]. Among the various particles in space, protons severely affect the solar cells [13]; therefore, studying on proton radiation response of multijunction solar cell is very important and interesting as it consists of different subcells with different radiation characteristics. Proton irradiation effects of solar cells with different particle energy have been studied in past decades [13–17]. Proton irradiation of GaInP/GaAs/Ge triple junction solar cell with different energy has been studied and displacement damage dose has been modified by using non-ionizing energy loss (NIEL) calculation [14]. Different energy proton irradiation of GaInP/GaAs/Ge solar cell has been simulated and the estimated electrical parameters of the cell showed very good agreement with the experimental results [15]. Radiation effects of GaInP/GaAs/Ge concentrator solar cells and their component subcells have been studied by 10 MeV proton irradiation, it turned out that the GaAs subcell exhibited the highest damage and radiation response of concentrator solar cell structures show similar results than those of traditional space solar cells [16]. The result of study on $<$ 200KeV proton irradiated GaInP/GaAs/Ge triple junction solar cell showed that the main limitation for cell performance comes from the middle GaAs subcell [17].

Although the radiation degradation characteristics of IMM multijunction solar cells have been investigated in some extent [18,19], the radiation effects of UMM multijunction solar cell and comparison to that of traditional LM cell are rarely reported. In this paper, we have studied the metal–organic chemical vapor deposition (MOCVD) grown UMM GaInP/GaInAs/Ge triple junction solar cells by irradiating with 3 MeV and 8 MeV protons. The degradation of electrical properties and spectral response of UMM cell have been discussed and compared to those of traditional LM GaInP/GaInAs/Ge triple junction solar cell.

## 2. Experimental techniques

All the samples studied in this work were deposited by an AIXTRON 2600G3 MOCVD reactor on epi-ready p-type 4-in. diameter Ge substrate with 9° offcut toward (111) from (100). Trimethylaluminium (TMAl), trimethylgallium (TMGa), and trimethylindium (TMIn) were used as group-III precursors, while phosphine and arsine were used as the group-V sources. Silane and diethyltellurium (DMTe) were used for n-type doping. Diethylzinc (DEZn) and carbon tetrachloride were used for p-type doping. The epilayers were grown at substrate temperatures between 600 °C and 700 °C at 50 mbar reactor pressure. A 3-µm-thick, 17 pairs of AlGaAs/GaAs and 17 pairs AlGaInAs/GaInAs, layer has been used as distributed bragg reflector (DBR) for LM and UMM cell, respectively. A 2-µm-thick, compositionally step-graded GaInAs with a strain gradient of 0.5%/µm, monolithic buffer layer was applied between DBR and Ge bottom cell in UMM structure. Devices were fabricated with conventional photolithograph processes. A two-layer $Al_2O_3$/$TiO_2$ antireflection coating was thermally evaporated. All the devices studied in this work are 4 cm × 6 cm in size and with begin of life (BOL) efficiency of ~30.5% for UMM cells and ~29.5% for LM cells under standard AM0 solar spectrum, respectively. Fig. 1(a) and (b) show the major structure of LM and UMM cells studied in this work, respectively. Proton irradiation was carried out by an EN tandem accelerator at room temperature. During the irradiation, the whole sample was placed into a uniform flux area without bias, when the irradiation finished the samples were transferred and kept in a lid box, the electrical and spectral measurements were carried out after a week. Two types of proton energy, 3 MeV and 8 MeV, have been used with a flux of $1.3 \times 10^9$ p/cm$^2$·s and $1.1 \times 10^9$ p/cm$^2$·s, respectively. Total irradiation proton fluences have been chosen based on nonionizing energy loss (NIEL) calculation.

High-resolution X-ray diffraction (XRD) was performed using a Panalytical X-pert Pro with a Ge 4-bounce (004) hybrid monochromator and PIXcel area detector, and the strain was determined by analysing reciprocal space maps (RSMs) of the asymmetric (115) reflection with X-ray incident in the (110) plane. Threading dislocation density (TDD) was estimated from cathodoluminescence (CL) image. Electrical parameters, including open circuit voltage ($V_{oc}$), short circuit current ($I_{sc}$), maximum output power ($P_{max}$) of solar cells were measured by Spectrosun X25A solar simulator under the standard test conditions (AM0, 136.7 mW/cm$^2$ at 25 °C). The external quantum efficiency (EQE) of solar cells was taken using a custom-build system.

## 3. Result and discussion

### 3.1. Compositionally graded buffer layer

Fig. 2(a) and (b) show an asymmetric (115) glancing exit RSM of UMM and LM cells, respectively. Fig. 2(a) indicates that the thin layers of the LM structure are fully strained. The $Ga_{.51}In_{.49}P$ and $Ga_{.99}In_{.01}As$ lattices are constrained to the Ge substrate lattice, so that the reciprocal lattice points of the layers and substrate are aligned in vertical direction (Qx axis). The RSM of UMM cell, shown in Fig. 2(b), illustrates that the lattice mismatched material, the $Ga_{.43}In_{.57}P$ top cell and the $Ga_{.92}In_{.08}As$ middle cell, are almost fully strain-free with a relaxation of ~95%.

During the growth of GaInAs compositionally graded buffer layers, the strain is mainly relieved by misfit dislocation. The portions of the dislocations parallel to the growth interface. Only a small number of threading dislocations have inclined to the growth interface and have been figured out in the active layers, which is confirmed by the CL measurement. Three different locations along the 4-in. diameter as-grown UMM epitaxial wafer were scanned via CL as shown in Fig. 3. The average TDD is counted as $\sim 1 \times 10^5$ /cm$^2$, which is in the same order of magnitude with TDD ($\sim 2 \times 10^5$ /cm$^2$ for metamorphic) of MM GaInP/GaInAs/Ge cells described in Ref. [20]. This relatively low TDD contributes to the high efficiency, especially for large area solar cells to maximize the carrier mobility and to minimize the current leakage.

### 3.2. Displacement damage dose ($D_d$) calculation

When a high energy particle passes through a material, it transfers energy to the crystal lattice through either ionization or atomic displacements. The atomic displacements, or displacement damage, such as vacancies, interstitials, etc., cause the degradation of the photovoltaic output of a solar cell due to the increase of recombination centers that degrade the minority carrier diffusion length. The displacement damage dose ($D_d$) approach is an effective analytical model for predicting the performance degradation of solar cells [21,22]. The displacement damage dose equals the product of irradiation fluence and the respective non-ionizing energy loss (NIEL), which can be calculated analytically based on the displacement interaction cross sections. NIEL is a quantity, unit of MeV·cm$^2$/g, that describes the rate of energy loss caused by atomic displacements when the particles traverse a certain material. The product of the NIEL and the particle fluence (time-integrated flux) gives the displacement damage energy deposition per unit mass of material. NIEL can be written as an integral over solid angle, as below equation,

$$\mathrm{NIEL}(E) = \int_{\theta_{\min(T_d)}}^{\pi} \left(\frac{d\sigma(\theta, E)}{d\Omega}\right) T(\theta, E) L[T(\theta, E)]\, d\Omega \tag{1}$$

where $\sigma(\theta,E)$ is differential cross section for atomic displacement, $T(\theta,E)$ the average recoil energy of the target atoms, $\theta_{min}(T_d)$ is scattering angle for which recoil energy equals the threshold for atomic displacement, $L[T(\theta,E)]$ is the Lindard partition factor.

Calculated NIEL values for proton and electron irradiation upon $Ga_{.5}In_{.5}P$, GaAs and Ge materials have been reported [23]. The result