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Measuring junction temperature of GaAs solar cells using pulse-width modulation photoluminescence

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ABSTRACT

A photoluminescence (PL) technique is presented to measure the junction temperature of GaAs solar cells. The technique utilizes the pulse-width modulation of excitation laser and the temperature dependence of PL spectra. The apparent change of PL energy on duty cycle can be advantageously used for the determination of the junction temperature. Varying the duty cycle from 10% to 75% causes an increase of 2.9 K in the junction temperature of GaAs solar cells. The carrier temperature of the junction layer was studied to confirm the result obtained from the pulse-width modulation PL.

High-efficiency solar cells have attracted considerable attraction due to their potential for space and terrestrial applications [1–3]. Efficient solar cell performance requires maximizing the light generated current, originating from optical generation in the absorber layer and the collection of the photogenerated carriers. One possible approach for increasing the light absorption is to concentrate the sunlight with concentrating mirrors or lenses. However, the temperature of solar cells increases under light-concentrating operations owing to the thermalization of the photogenerated carriers. With an increase of cell temperature, the open circuit voltage of photovoltaic cells decreases, leading to a decrease of conversion efficiency [4–7]. Solar cells will also exhibit long-term degradation if the temperature exceeds a certain limit [8,9]. Thus, the cell temperature of the solar cells has to be properly characterized particularly when cells are operated at high concentrations. It is therefore important to develop a method for measuring the cell temperature of solar cells. An approach to obtain the cell temperature of solar cells has been reported recently [10]. In order to determine the cell temperature from experiments a one-dimensional model based on energy balance equations were used [10]. According to Ref. [10], the incoming concentrated solar flux is equivalent to summation of the electric power output as well as heat loss from radiation, natural convection, and the cooling system. Under thermal equilibrium, the cell temperature can thus be determined by balancing the rate of energy generation with the rate of energy loss. However, the evaluation of cell temperature from the above method involves measurements through contacts. It is desirable to develop a rapid, non-destructive, and non-contacted method to characterize the junction temperature of solar cells.

Recently, a technique using pulse-width modulation has been used in LEDs to investigate the junction temperature of LEDs [11,12]. The junction temperature has been determined by comparing temperature-sensitive LED parameters (e.g., the threshold current and/or wavelength of emission peak) under pulsed operation of electric power. However, the above method is not suitable for solar cells since change of the injection current may produce temporary but undesirable changes in the p–n junction. In this study, we introduce a technique for measuring the junction temperature of solar cells using the pulse-width modulation photoluminescence (PL). This technique measures the duty-cycle-dependent PL under the pulse-width modulation of excitation laser. The junction temperatures were calibrated from the temperature-dependent PL measurements by calculating heat transfer in the solar cells.

The GaAs solar cells were grown by metal–organic chemical vapor deposition (MOCVD) on p-type Ge substrates. The GaAs

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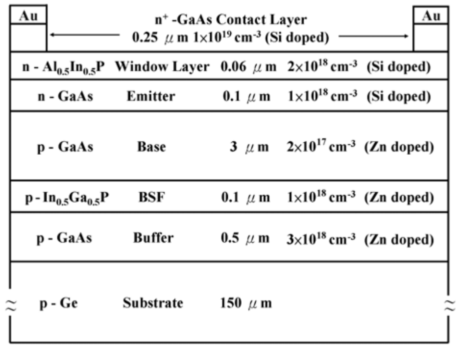

Fig. 1. Schematic cross section of the investigated GaAs solar cell.

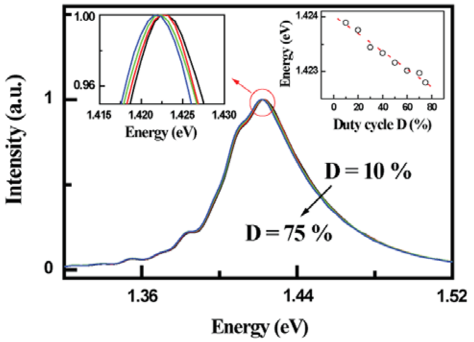

Fig. 2. Normalized PL spectra of GaAs solar cells at different duty cycles (D) at room temperature. The left inset displays the enlarged PL peaks at different duty cycles. The open circles in the right inset indicate the PL peak energy of GaAs solar cells with rising duty cycle (D). The dashed line in the right inset shows the linear fitting of experimental data.

buffer layer and the InGaP back surface field (BSF) layer were first grown at the substrate, followed by a 3 μm thick p-type GaAs base layer, 100 nm n-type emitter layer, 60 nm AlInP window layer, and 250 nm GaAs contact layer. The Zn-doped p-type (Si-doped n-type) concentration was between 2×10^{17} to 3×10^{18} cm^{-3} (1×10^{18} to 1×10^{19} cm^{-3}). The schematics of the GaAs solar cell were shown in Fig. 1. In this study, the PL measurements were carried out by the CW solid state laser with wavelength of 532 nm and modulated with a square-shaped pulse at a frequency of 10 Hz. The duty cycle of square waves is defined as $D = t/T$, where t is the width of the square pulse and T is the period. The duty cycle within a range of 10% to 75% was controlled by a function generator (HP-8112A). The PL signal was focused into a 0.75 m monochromator whose output was detected by a silicon detector. For the temperature-dependent measurements, the GaAs solar cells were mounted on the copper sample holder in a close-cycle helium cryostat. For measuring conversion efficiency of solar cells, I–V characteristics of the solar cells were measured with a source meter (Keithley-2400) under simulated AM1.5 irradiation (100 mW/cm^2) from a solar simulator (WACOM, WXS-130S-L2+).

Fig. 2 plots the PL spectra of GaAs solar cells as a function of duty cycle at room temperature. The left inset in Fig. 2 displays the enlarged PL peak for the duty cycle from 10% to 75%. The energy of PL peak occurred at 1423.8 meV when the duty cycle is at 10%. As the duty cycle is increased, the peak energy shifted toward the low-energy side. This phenomenon is explained by the increase of the temperature due to the increased heating by the increase of laser power. The heating effect would be different at different laser power. With the excitation of laser power of 109 mW, varying duty cycle from 10% to 75% causes a shift of 1.2 meV in energy in the PL of GaAs. The open circles in the inset of Fig. 2 show the peak energy (E) versus duty cycle (D). The dashed line in the right inset of Fig. 2 shows the linear fitting of experimental data and the slope is $dE/dD = 0.615$ meV/%. The linear dependence of PL peak energy on duty cycle can be advantageously used for determination the junction temperature in solar cells.

To find out the junction temperature, we need to calibrate the effect of heating to the energy change of PL peak by measurements of the dependence of PL on temperature. The inset in Fig. 3 shows the temperature-dependent PL of the GaAs solar cells from 200 to 300 K, as indicated the arrow. The peak of the PL is red-shifted with the temperature due to band gap shrinkage. The energy of the PL peak in the GaAs solar cell as a function of temperature are presented in the open circles of Fig. 3. It is noted that the temperature of the PL was detected from the copper sample holder (heat sink), which contacts directly to the substrate of the solar cell. To obtain the junction temperature of solar cells, heat transfer of the solar cell was analyzed. In general, the heat transfer from a temperature difference by thermal conduction can be expressed as

$$\Delta T = T_j - T_0 = R_{th} \cdot Q, \tag{1}$$

where T_j is the junction temperature, T_0 is the reference temperature (substrate temperature), R_{th} is the thermal resistance, and Q is the thermal power dissipation. R_{th} of this GaAs solar cell can be estimated from [13]

$$R_{th} = \rho(\ell/A), \tag{2}$$

where ρ is thermal resistivity, ℓ is the thickness of the solar cell in the direction of heat flow, and A is the cross sectional area of the medium through which heat is flowing. The thermal resistivity (ρ) of the GaAs, InGaP, and Ge layers for our GaAs solar cell were obtained to be 1.72, 1.81 and 19 cm K/W, respectively [14].

In order that Q actually represents the heat dissipated in the junction, the optical power absorbed by the junction layers P_a should be calculated. Since the incident optical power P_i is consumption by a loss at the surface and interfaces, P_a can be obtained from P_i by using the matrix formulation for multi-layer structures [15]:

$$\begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} = D_0^{-1} \cdot D_1 \cdot P_1 \cdot D_1^{-1} \cdot D_2, \tag{3}$$

where D_0, D_1, and D_2 are the dynamic matrices for free space, AlInP, GaAs, respectively; P_1 is the propagation matrices for AlInP window layer. We assume that all absorbed radiation (P_a) that is not converted into electric output by the cell must be dissipated as heat loss to the cell. The heat absorbed by the cell causes a rise in cell temperature $\Delta T'$. The equation governing this relation is described as:

$$Q = P_a - \eta P_i, \tag{4}$$

where η is conversion efficiency. It is well known that η decreases with an increase of temperature [3,4]. This indicates that the above equations are made a little complex because $\Delta T'$ itself is a function of the efficiency. The relation that governs the temperature dependence of conversion efficiency is described by [10]

$$\eta = a(1 - b \cdot \Delta T'), \tag{5}$$

where a is the cell efficiency under room temperature and b is the cell temperature coefficient. To find out a and b, the photovoltaic I–V characteristics under AM1.5 global solar spectrum under different temperatures were measured. Fig. 4 shows the temperature dependence of I–V characteristics of our GaAs solar cells. The open circuit voltage decreases with increasing temperatures owing to the increases of the saturation current [4]. The short-circuit current of the GaAs solar cells increases a little with increasing temperatures. On the other hand, the fill factor decreases with temperature [5]. Originating from the decrease of open circuit voltage and fill factor, the conversion efficiency

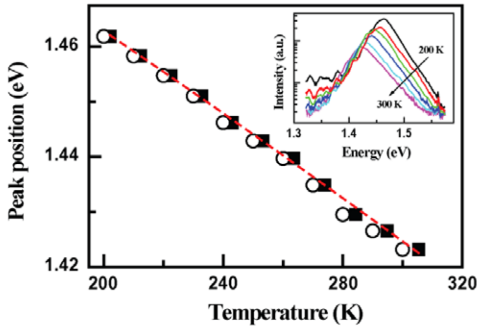

Fig. 3. The open circles and closed squares indicate the dependence of PL peak energies on the substrate and junction temperatures of GaAs solar cells, respectively. The dashed line displays the result calculated using Eq. (6). The inset shows the temperature-dependent PL spectra from 200 to 300 K.

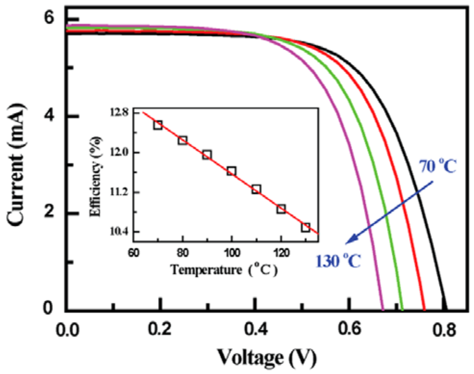

Fig. 4. Current–voltage curves of GaAs solar cells at different temperatures. The inset shows the conversion efficiency of GaAs solar cells as a function of temperature.

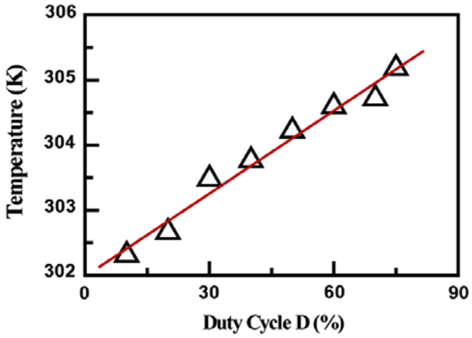

Fig. 5. The junction temperature of the GaAs solar cells versus the duty cycle (open triangles). The solid line is the linear fitting of experimental data.

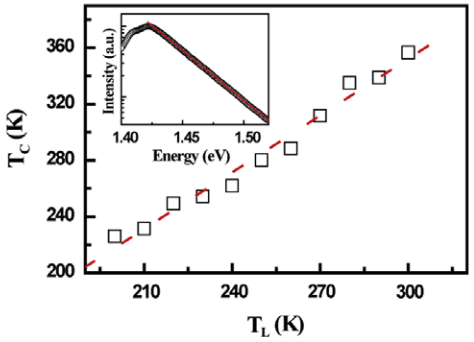

Fig. 6. The carrier temperature (T_C) as a function of the lattice temperature (T_L). The dashed line represents proportionality between T_C and T_L. The inset shows the high-energy tail of the PL in the junction layer for the duty cycle of 75%. The solid line in inset displays the slopes of the high-energy tail.

decreases with temperature as shown in the inset of Fig. 4. The figure shows a linear decrease of the conversion efficiency with temperature. With the fit using Eq. (5), we obtained $a = 14.3\%$ and $b = -0.034\ \mathrm{K}^{-1}$.

The junction temperature T_j of the GaAs solar cell can thus be calculated by combining Eqs. (1) and (3)–(5). Taking $P_i = 109$ mW, $P_a = 65.7$ mW, and $\eta = 14.3\%$, we obtain junction temperature T_j for the solar cell. The energies of the PL peak in the GaAs solar cell as a function of the junction temperature are displayed by the closed squares in Fig. 3. It was found the junction temperature is higher than the substrate temperature by about 2–4 K. The redshift of PL peak energy as a function of the junction temperature can be analyzed according to the Varshni equation [11,16]:

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T + \beta}, \tag{6}$$

where $E_g(0)$ is the energy band gap at 0 K, and α and β are the Varshni parameters. At the high-temperature region, the effect of band gap shrinkage shows the linearity with temperature in the Varshni equation [11]. According to Eq. (6), the PL peak was plotted with the junction temperature, as shown in the dashed line of Fig. 3. From the fit, α and β were found to be 0.5 meV/K and 188 K, respectively, which are consistent with the reported values in GaAs [17]. From the slope of the dashed line in Fig. 3, the $\mathrm{d}E/\mathrm{d}T$ value of PL was calculated to be 0.4 meV/K. This slope is used for evaluating the junction temperature from measurements of the pulse-width modulation PL.

The open triangles in Fig. 5 display the junction temperature of the GaAs solar cells as a function of the duty cycle. As can be seen, the temperature rise measured by this technique is proportional to the duty cycle, indicating the measurement is sensitive to the dissipated optical power. Varying the duty cycle from 10% to 75% causes a rise of 2.9 K in junction temperature. The solid line in Fig. 5 is a linear fit to the experimental data. The duty cycle coefficient ($\mathrm{d}T_j/\mathrm{d}D$, where T_j is the junction temperature) of the junction temperature is 0.045 K/% under the excitation of laser power of 109 mW. Such a type of linear relation reveals that the influence of the pulse-width modulation of optical power on the junction temperature of the GaAs solar cells is effective and has sufficient temperature resolution.

Recently the carrier temperature (T_C) of PL has also been used to investigate the junction temperature of a device [12]. To confirm the accuracy of the above method we studied T_C of the junction layer in our GaAs solar cells. In the process of PL, the photoexcitation creates energetic electrons in the conduction band, which relax toward less energetic state by transferring energy to the lattice (via the electron–phonon scattering) and other electrons (via the electron–electron scattering). If the electron–electron collision rate is larger than the phonon emission rate, the non-equilibrium electron population in the electron gas relaxes towards a Boltzmann–Maxwell distribution and can be characterized by the T_c which is higher than the lattice temperature (T_L) [12]. The inset of Fig. 6 shows the high-energy tail of PL for GaAs junction for the duty cycle of 75%. The spectrum show that the high-energy tail of PL decreases exponential with photon energy, revealing that the PL is related to the hot carrier recombination. The high-energy tail of the PL can be analyzed by the function [12]:

$$I(\hbar w) \sim \exp(-\hbar w/kT_C), \tag{7}$$

where T_C reflects the carrier temperature of the thermalized electrons. The obtained T_C for the duty cycle of 75% was found to be 356.7 K from the fit of the high-energy tail of PL, as shown in the solid line of the inset of Fig. 6. For determining the lattice temperature (T_L) from T_C, we calibrated the relationship between T_C and T_L by measurements of the dependence of PL on temperature by fitting the high-energy tail of PL. Fig. 6 shows the interrelation between T_C and T_L of the GaAs junction layer from 200 to 300 K. T_C of the junction layer linearly correlate with T_L, as shown in the dashed line in Fig. 6. We used this proportionality to estimate T_L of the GaAs junction layer and a value of 305.0 K was obtained. According to the method of our pulse-width modulation, the junction temperature for the duty cycle of 75% is 305.2 K. The good agreement is an indication that the technique with the pulse-width modulation PL can be used as a convenient tool to measure the junction temperature of solar cells.

In summary, we determined the junction temperature of GaAs solar cells using pulse-width modulation PL. The junction temperature of solar cells is calibrated from the substrate temperature according to the heat transfer in solar cells. A linear relation between the junction temperature and the duty cycle was found. We also studied the carrier temperature of the junction layer to confirm the result determined from the pulse-width modulation PL. The method described in this paper is useful and convenient and it can be applied for the evaluation of thermal characteristics in solar cells.

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