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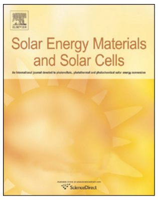

Effects of copper diffusion in gallium arsenide solar cells for space applications

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ABSTRACT

High efficiency, thin-film Epitaxial Lift-Off (ELO) III–V solar cells offer excellent characteristics for implementation in flexible solar panels for space applications. However, the current thin-film ELO solar cell design generally includes a copper handling and support foil. Copper diffusion has a potentially detrimental effect on the device performance and the challenging environment provided by space (high temperatures, electron and proton irradiation) might induce diffusion. It is shown that heat treatments induce copper diffusion. The open-circuit voltage (V_{oc}) is the most affected solar cell parameter. The decrease in V_{oc} can be explained by enhanced non-radiative recombination via Cu trap levels in the middle of the band gap. The decrease in V_{oc} is found to be dependent on junction depth. In all Cu cells annealed at $T \geq 300$ °C signs of Cu diffusion are present, which implies that a barrier layer inhibiting Cu diffusion is necessary. Electron radiation damage was found to have no influence on Cu diffusion.

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1. Introduction

With the Epitaxial Lift-Off (ELO) technique III–V solar cell structures can be removed from their growth substrates, utilizing a sacrificial $Al_xGa_{1-x}As$ layer that can be removed by a selective etch process [1,2]. In this way thin, lightweight and flexible solar cells are created, with efficiencies equivalent to or even larger than substrate based solar cells [3–6]. These characteristics make ELO III–V solar cells excellent candidates for implementation in solar panels for space applications [7]. Due to the additional flexibility new light-weight panel designs become available [8] and the launch costs would be reduced due to the lower weight. The ELO process allows for re-use of the expensive GaAs or Ge substrates [3,9], which would reduce the cost of the cells themselves as well. At the same time the challenging environment provided by space (vacuum, UV irradiation, high energy electron and proton irradiation, temperature cycling) imposes additional challenges in thin-film solar cell design and preparation.

The main potential disadvantage of our current thin-film ELO gallium arsenide solar cell design is that it includes a copper handling and support foil [8]. Copper is notoriously known as a fast diffuser in many semiconductors, including GaAs. It is generally assumed that diffusion of Cu into a semiconductor device has detrimental effects on the operation of such a device, most likely because Cu introduces a trap level in the band gap [10]. Such a trap level is a potential non-radiative recombination pathway [11,12]. However, while Cu diffusion and the effects of Cu in large semiconductor crystals are described elaborately in the literature [13–29], there is virtually no literature on the effects of Cu diffusion on semiconductor devices such as solar cells.

The scarce literature available on the device performance under influence of Cu diffusion may involve deliberate doping of the semiconductor material with Cu [30] or incorporation of Cu during preparation of the semiconductor material itself [31–33]. Such approaches are not useful if one wants to understand what happens when copper (or an other impurity) enters the III–V solar cell material gradually over time. Secondly, there is the issue of material quality. Already in 1974 Hasegawa et al. found that diffusion in large semiconductor crystals is more pronounced than in epitaxial layers [34], most likely due to the better crystal quality of the latter. As material quality of epitaxial GaAs has been strongly improved by the introduction of MOCVD, it may well be that a traditional description of Cu diffusion in large GaAs crystals is not applicable to a modern MOCVD grown GaAs solar cell.

From the challenging conditions provided by space, the temperature cycles (particularly the higher maximum temperature 70–100 °C) are most likely to enhance copper diffusion, as diffusion

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is known to be strongly temperature dependent [25]. Additionally electron and proton irradiation may also affect copper diffusion, since electron and proton irradiation create defects in the solar cell material [35] and diffusion in large semiconductor crystals is known to depend on interaction with vacancies [16]. Therefore it seems plausible that an increased amount of defects (such as vacancies) enhances Cu diffusion. UV irradiation and vacuum, the other typical space conditions, are assumed to have no influence on the diffusion process. UV irradiation is expected to affect mainly the protective cover glass and the vacuum is generally associated with delamination issues.

Depending on the exact mission requirements a space solar panel is expected to operate properly for at least 10–15 years in space. This means that for testing purposes the ageing process needs to be accelerated. For irradiation tests the usual approach is to expose solar cells to a dose equivalent to the dose experienced during 15 years in space [35,36]. But for investigation of temperature effects, there is not such a standard approach. In general elevated temperature accelerated life testing is assumed to be an excellent method to mimic the ageing of a device. It is assumed that operation over a long period of time at a (relatively) low temperature is equal to operation for a much shorter time at a higher temperature. This can be described with an Arrhenius model [37]:

$$\frac{t(T_{\mathrm{use}})}{t(T_{\mathrm{acc}})} = \exp\left[\frac{E_a}{k}\left(\frac{1}{T_{\mathrm{use}}} - \frac{1}{T_{\mathrm{acc}}}\right)\right], \qquad (1)$$

in which T_{use} is the (average) temperature at which the device will be used and T_{acc} is the temperature of the accelerated life test, k is the Boltzmann constant, E_a is the activation energy and $t(T_{\mathrm{use}})$ and $t(T_{\mathrm{acc}})$ are the times t at T_{use} and T_{acc} after which the device has reached a predefined amount of degradation.

The main issue with this method is that determination of the activation energy is time consuming and requires a large number of samples, hence there are very few activation energies reported in the literature. Núñez et al. reported an E_a of 1.02 eV for GaAs concentrator cells [37], which are operated at an elevated working temperature of 65 °C under concentrated light, this seems a good first estimate for the activation energy. However, the ECSS standard for photovoltaic assemblies and components (ECSS-E-ST-20-08C [38]) advises to calculate the accelerated life test parameters for solar cell assemblies (cell with cover glass, interconnect and by-pass diode) assuming an activation energy of 0.7 eV, which would result in higher test temperatures or longer test times.

The average working temperature and the time in space depend on the exact type of application of the solar panel. For a LEO (Low Earth Orbit) mission the maximum temperature is 100 °C and the typical time in orbit is 10 years (0.876×10^5 h), for a GEO (Geosynchronous Earth Orbit) the maximum temperature is 70 °C and 15 years (1.314×10^5 h) in orbit is common practise. With Eq. (1) accelerated test times ($t(T_{\mathrm{acc}})$) can be calculated. For activation energies of 0.7 eV and 1.02 eV the accelerated test times at various test temperatures are given in Table 1 for a GEO mission (15 years, 70 °C), a LEO mission (10 years, 100 °C) and an extreme case (15 years, 100 °C).

Table 1 shows that low test temperatures (200 °C) require test times of many days, which is too time consuming for initial tests. Test times are significantly reduced at high test temperatures (400 °C), but at such temperatures the induced damage might not be related to Cu diffusion (alone). Diffusion processes depend exponentially on temperature so at higher temperatures other diffusion processes might start to play a significant role as well. For example dopant diffusion (particularly Zn) and gold diffusion. Any of this additional diffusion damage should be observed for all GaAs solar cells regardless of the metals present in the contact. Since we observe some damage to cells with plain gold contacts at 400 °C (see Section 3.2) we took this as a maximum temperature to be used. Ideally a temperature somewhere in between (as low as possible) should be used. With the 1.02 eV activation energy all three scenarios (GEO, LEO, extreme) are covered with 4 h at 300 °C, hence it was assumed to be a suitable first test. If no diffusion effects are observed the test can easily be extended to a few days in order to cover all scenarios with an activation energy of 0.7 eV.

Table 1
Accelerated test times at various accelerated test temperatures for GEO (15 years, 70 °C) and LEO (10 years, 100 °C) missions and for an extreme scenario (15 years, 100 °C) for activation energies of 0.70 eV and 1.02 eV. Values are presented in days if larger than 24 hours, in minutes if smaller than 1 hour and in seconds if smaller than 1 minute. All values were rounded off towards the next 0.5 second/minute/hour/day so the test time is always overestimated.

	200 °C	250 °C	300 °C	350 °C	400 °C
$E_{\mathrm{act}} = 0.70$ eV					
GEO	8.5 days	2.0 days	10.0 h	3.5 h	1.5 h
LEO	37.0 days	7.5 days	2.0 days	14.5 h	6.0 h
Extreme	55.0 days	11.0 days	3.0 days	21.5 h	8.0 h
$E_{\mathrm{act}} = 1.02$ eV					
GEO	10.0 h	55.0 min	8.0 min	1.5 min	22.0 s
LEO	4.5 days	10.0 h	1.5 h	15.5 min	4.0 min
Extreme	7.0 days	15.0 h	2.5 h	23.5 min	6.0 min

In order to check whether Cu-foil based ELO thin-film GaAs solar cells are suited for applications in space, it is important to gain more understanding of the effects that exposure to the space environment will have on Cu diffusion in GaAs solar cells. In preparatory experiments which will be described in Section 3.1, it was found that ELO cells are not suited for heat treatments at temperatures ≥250 °C. However, lower temperatures require annealing times of many days (see Table 1) in order to simulate 15 years in space. Therefore regular substrate based GaAs solar cells were used to investigate the effects of Cu diffusion on the cell performance. In order to do so the substrate cell structures were adapted to provide a geometry that closely resembles that of ELO cells. This is a valid alternative since copper diffusion is dependent on the material [25], which is GaAs for both thin-film and substrate-based solar cells and the material quality [34], which is equal as both types of structures are grown by the same MOCVD process and perform equally well [4]. For final qualification of ELO thin-film solar cells actual thin-film structures should be used, but for study of potentially damaging processes substrate-based alternatives can be used as long as the studied process is not expected to be dependent on the thin-film nature of the ELO cells.

A standard ELO thin-film (~2 μm) GaAs solar cell (see Fig. 1a) is typically produced with a ~100 nm gold back contact and a ~15 μm copper handling and support foil. Copper was chosen because it is cheap and compatible with all post-ELO processing steps and allows for easy contacting of the solar cell. Simply applying a similar contact scheme at the back of a substrate solar cell (see Fig. 1b and c) would not be representative for the ELO cell configuration, as the copper would have to diffuse through ~300 μm of GaAs before reaching the cell (which has a thickness of only a few μm). Thus the copper has to be applied on the front contact (thick layer of Cu on thin Au contact). Normally the front contact only covers a few percent of the solar cell surface, which is clearly different from a completely covered back surface. On the other hand it is also not possible to cover the front of the cell completely, because then light can no longer enter the cell and hence there would be no working device that can be tested. As a compromise between these two extremes a front contact grid pattern with nearly 50% coverage was designed (see Fig. 2),

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