# IMPROVING THE BACK SURFACE REFLECTION OF GERMANIUM THERMOPHOTOVOLTAIC CELLS USING LASER FIRED CONTACTS

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ABSTRACT: Using the knowledge of the recently realised stand-alone germanium solar cells for application as bottom cell in mechanically stacked solar cells, germanium TPV cells have been realised. To increase the cell response in the high wavelength region, which is needed in thermophotovoltaic systems, an innovative back-side contacting mechanism has been developed. In order to increase the back surface reflection properties of the cell, laser fired contacts have been optimised and used. By optimising the applied laser power, a backcontact with a specific contact resistance of $7.6 \cdot 10^{-4}\ \Omega \cdot cm^{-2}$ has been fabricated. Using this contact, a germanium thermophotovoltaic cell with an AM1.5 energy conversion efficiency of 6.3 percent has been realised, showing a higher response at high wavelengths compared to the classical germanium solar cell.

Keywords: thermophotovoltaics, light trapping, germanium

## 1 INTRODUCTION

At IMEC stand-alone germanium solar cells for application as a bottom cell in mechanically stacked multi-junction solar cells have been developed [1]. Using a hydrogen-rich amorphous silicon passivation a world class conversion efficiency of 8.4 percent (AM1.5, 1 sun) has been achieved with a $V_{oc}$ of 258 mV, a $J_{sc}$ of 50 $mA \cdot cm^{-2}$ and a fill factor of 65 percent [1].

Germanium is well suited for use in TPV systems as it has a low bandgap of 0.66 eV and a relatively low cost compared to other low-bandgap semiconductors. Existing knowledge available at IMEC of classical germanium solar cells is used to realise a highly efficient germanium thermophotovoltaic cell.

Comparing a photovoltaic and a TPV system, two basic differences are important. First of all, in a thermophotovoltaic system the incident spectrum has a peak at higher wavelength due to the low temperature (1500K) of the heat source compared to the sun. Secondly, as a result of the small distance between heat source and photovoltaic cell compared to a photovoltaic system, a high current density will be generated. Where the high current density has implications on the contact requirements, the high wavelength of the incoming photons makes the application of light trapping necessary to obtain high absorption.

This paper gives the results on the first tests that have been done in order to obtain enhanced light trapping by fabricating a highly reflective backside. In the classical germanium solar cell an annealed aluminium back-contact is used [2] which has a low reflection of about 20 percent for high wavelengths, due to the formation of an eutectic layer during the annealing, which roughens the back surface.

One method to enhance the reflective properties is to use a metal layer like aluminium without an extra annealing step. In classical germanium solar cells this anneal step is used to locally dope the p-type substrate such that a $p^+$ BSF is formed that passivates the backside. Using a non-treated aluminium layer, passivation can be achieved by the application of an amorphous silicon layer which is also used for front-surface passivation and is transparent for the incident light in a thermophotovoltaic system.

Since amorphous silicon itself is insulating, the backside contact must be realised through the amorphous silicon passivation layer. In this research the contact is obtained by local heating of the aluminium layer by means of a laser. As a result of using aluminium at the backside a local BSF is formed near the contact resulting in a fully passivated backside.

This paper describes the progress that has been obtained in realising a germanium thermophotovoltaic cell, using laser fired contacts. In paragraph 2 the processing of such a cell is discussed where in paragraph 3 the results of the performed measurements and simulations are discussed.

## 2 CELL FABRICATION

The cell process that has been developed consists of 7 basic steps. A schematic overview of the cell process is shown in Figure 1.

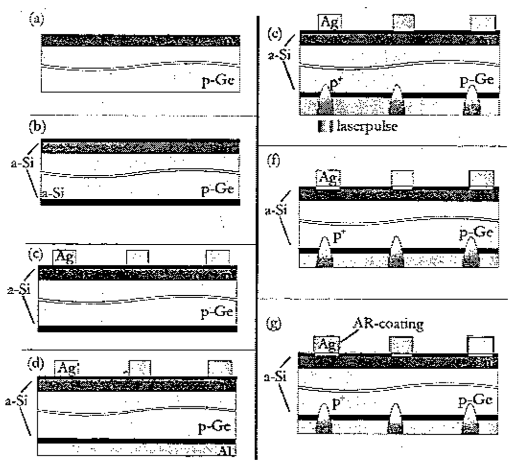


**Figure 1:** Overview of cell process of a germanium cell suited for application in a thermophotovoltaic system.

Starting with a bare p-type, 145 μm thick, 4-inch germanium substrate, first an $n^+$ emitter is realised by diffusion of phosphorous from a spin-on dopant which is applied by spin coating, see Figure 1(a). The diffusion profile is optimised by changing the phosphorous concentration in the spin-on dopant, the spin speed and the diffusion temperature and time [3].

A crucial step for obtaining high cell efficiencies is the passivation of the front and back surface, Figure 1(b). A thin layer of amorphous silicon is deposited by application of Plasma Enhanced Chemical Vapour Deposition (PECVD). The surface pre-treatment and plasma conditions are of crucial importance for the quality of amorphous silicon passivation [4].

Subsequently, a palladium (Pd)/silver (Ag) stack is used as a front contact, see Figure 1(c), where Pd will diffuse through the amorphous silicon layer. The additional layer of silver is used to realise a low series resistance contact. Using this technique, a FF of 68.5 percent with a $V_{oc}$ of 255 mV under AM1.5 conditions has been achieved.

To realise the highly reflective back contact, aluminium will be applied, see Figure 1(d).

As a next step, contact at the backside will be realised by local heating with a laser. Using this technique the aluminium layer is locally heated and contact is being made.

Subsequently, an annealing is done to diffuse the palladium through the amorphous silicon layer and to anneal the laser fired contact. Optimisation of the annealing time is crucial since a too short time does not leave a contact and a too long time results in a shorted cell.

As a final step, a dual layer anti-reflective coating consisting of ZnS and $MgF_2$ is deposited to increase light transmission into the germanium.

## 3 RESULTS

### 3.1 Reflection measurements

Measurements have been done, where the reflection as function of the wavelength has been measured from the front side of the sample, for germanium substrates having an anti-reflective coating and different backside contacts, as shown in Figure 2.

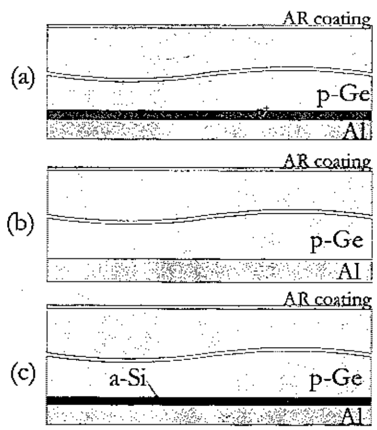


**Figure 2:** Overview substrates for different reflection measurements.

The results of these measurements are given in Figure 3 where one can see the low reflective properties of a diffused aluminium backside contact (see Figure 2 (a)). This can be explained by the fact that an Al-Ge eutectic layer is formed during the annealing which roughens the back surface, leading to a lower reflectance at the backside. Application of an aluminium layer without annealing leads to an increase of the (total) reflection at high wavelengths up to 50 percent. Since no BSF is formed in this situation, an alternative backside passivation technique needs to be applied.

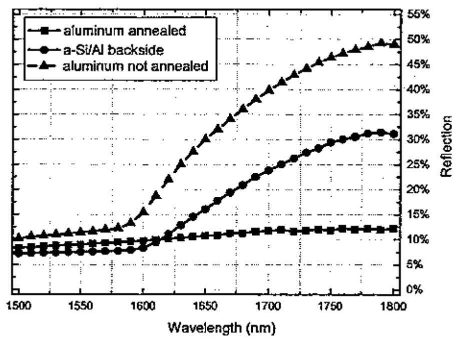


**Figure 3:** Measurement of the reflection of germanium substrates with different metals at the backside.

Since germanium surface passivation using PECVD amorphous silicon has proven to be effective, also the backside is passivated with amorphous silicon. Using an a-Si/Al backside contact, a reflection of 30 percent at 1800 nm is measured which is over 18 percent absolute increase compared to an annealed aluminium contact. It is expected that a higher reflectance can be realised by optimising the thickness of the amorphous silicon layer. Using this structure, contact can be made using so-called laser fired contacts (LFC), which is discussed in more detail in the next section.

### 3.2 Laser fired contacts

An innovative method to realise local contacts on a germanium substrate through an insulating layer like amorphous silicon is by laser firing. In Figure 1 the process for realising Laser Fired Contacts (LFC) [5] is shown. After passivating the backside using PECVD amorphous silicon an aluminium contact layer is deposited by evaporation. Subsequently the metal will be heated locally using a laser. For this application a green (532 nm) YAG laser is used. Local heating results in the formation of an eutectic compound between aluminium and germanium, forming the contact.

Aluminium is most suited because a local $p^+$ layer is obtained near the contact that serves as a back surface field. Aluminium also shows highly reflective properties as shown in Figure 3.

In first experiments, the laser power applied on the substrate has been optimised by changing the laser current through the laser diode, the propagation speed of the laser head and the focus of the beam. By changing the focus, the applied power can be spread over a larger area which results in a larger contact area.

In Figure 4 a SEM image of a cross-section of the contacted area is shown. A clear change of structure at the laser-heated area is visible. Transfer Length Method (TLM) measurements, has been applied to verify that an Ohmic contact has been formed with a specific contact resistance of $7.6\cdot10^{-4}\ \Omega\cdot cm^{-2}$.

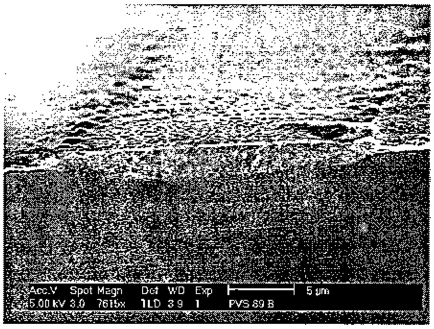


**Figure 4:** SEM image of Laser Fired Contact between germanium and aluminium.

3.3 Simulation results of contact structure

Using an analytical model [6], together with PC1D [7] as simulation tool, the optimal contact structure at the backside of the TPV cell has been calculated. For this simulation a contact pattern existing of dots has been used where different surface recombination velocities have been assumed. At the contacted and non-contacted area an effective surface recombination velocity of $5\cdot10^4\ cm\cdot s^{-1}$ and $20\ cm\cdot s^{-1}$ is taken respectively. This large difference is due to the damage that occurs during contact formation.

The simulation has been done by calculating the energy conversion efficiency by varying the metallisation fraction $f$ at the back-side which is defined as:

$$f = \pi\frac{r^2}{p^2} \qquad (1)$$

with $r$ being the point radius and $p$ being the period length of the pattern. Since these cells will be used in a thermophotovoltaic system, the spectrum emitted by an $Er_2O_3$ selective emitter is used in this simulation.

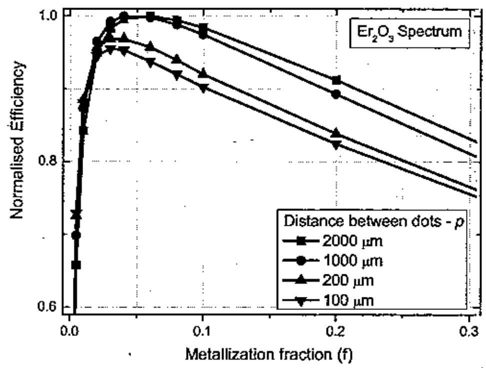


**Figure 5:** Results of the simulation where the efficiency as function of the metallisation fraction ($f$) for several distances between the dots ($p$) has been calculated.

The results of the simulations are shown in Figure 5. One can conclude that a dotted pattern, where the distance between the dots is about 1-2 mm with a total metallisation fraction of 0.05 gives the best results. The influence of the high surface recombination velocity near the contact pads is the reason for this optimal contact structure. This is due to the fact that a contact pad with a big area leaves a large distance between the contacts with a low surface recombination velocity.

3.4 Cell Results

Since the used laser is not powerful enough to form the large area (r ~ 100 µm) dotted contacts on the backside of the cell, first solar cells have been realised using a pattern consisting of lines. These lines have a width of 20 µm and a spacing of 500 µm which leads to a total metallisation fraction of 0.05 which was calculated to be the optimum.

In Table I, the results of 2 fabricated 1 x 1 $cm^2$ solar cells, A and B are given, for different front-contact annealing times [3] and with an additional dual layer anti-reflective coating consisting of ZnS and $MgF_2$.

**Table I:** Overview Cell Results of germanium TPV cells, measured using the AM1.5 spectrum, 1 sun.

| # | total diffusion time | ARC | $V_{oc}$ (mV) | $J_{sc}$ ($mA/cm^{-2}$) | FF (%) | η (%) |
|---|---|---|---|---|---|---|
| | 5 min | No | 251.1 | 14.1 | 18.6 | 0.7 |
| A | 20 min | No | 234 | 35.2 | 47.1 | 3.9 |
| | 20 min | Yes | 244 | 44.8 | 53.6 | 5.6 |
| | 5 min | No | 246.6 | 34 | 44.3 | 3.7 |
| B | 20 min | No | 243 | 35.1 | 60.3 | 5.1 |
| | 20 min | Yes | 243.1 | 44.5 | 58.5 | 6.3 |

For cell B, the IV characteristics measured at the three different stages is given in Figure 6. These measurements show the formation of the contact at the front by annealing the solar cell. After 5 minutes in 240 °C using Forming Gas (FOG), in cell A no contact was observed but in cell B contact has been realised but still with a low fill-factor due to a high series resistance, as shown in Figure 6. After a second annealing of 15 minutes, contact has been formed in both cells and a large improvement of the fill-factor was measured, but local shunting of the emitter is expected since the fill factor is non-optimal due to a lowered shunt resistance. It is expected that a total diffusion time of 20 minutes was a bit too high for this specific solar cell.

After applying the anti-reflective coating for both cells an improvement of the current was observed without a significant decrease of the fill factor which proves the quality of this contact.

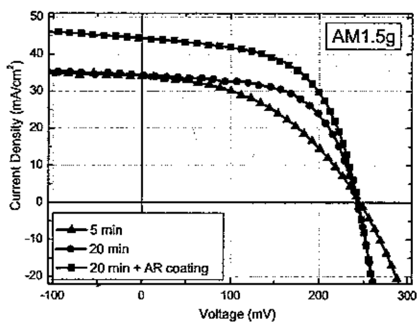


**Figure 6:** IV-characteristics of the germanium LFC solar cell B.

Cell B resulted in an AM1.5 efficiency of 6.3 percent with a short circuit current density ($J_{sc}$) of 44.5 mA·cm$^{-2}$, an open circuit voltage ($V_{oc}$) of 243.1 mV and a fill-factor (FF) of 58.5 percent. Figures 7 and 8 show the quantum efficiency curves of cell B demonstrating the improved response of this cell in high wavelength regions.

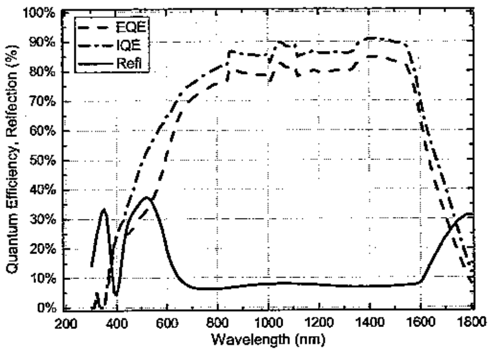


**Figure 7:** Quantum efficiency of a germanium TFV cell (cell B) using LFC back contact.

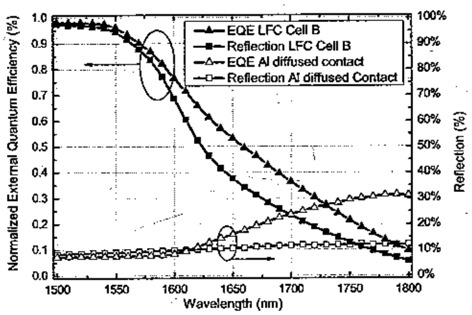


**Figure 8:** Normalised external quantum efficiency (EQE) and reflection of a laser fired (cell B) and a classical contacted germanium solar cell.

The most important motivation for using laser fired contacts in germanium TPV cells is the higher reflectance and thus higher spectral response for incoming photons with high wavelengths. In our "standard" germanium solar cells an aluminium diffused back contact is used. In Figure 8 the reflectance and normalised EQE which has been measured on the 2 different types of germanium solar cells has been compared. Each cell has the same emitter and front contact grid, but one cell has a diffused aluminium rear contact and the other a LFC contact. One can observe a better EQE for high wavelengths in combination with a higher reflectance. These two improvements lead to a higher efficiency in TPV systems, which was basically the purpose of applying laser fired contacts in germanium.

## 4 CONCLUSIONS

The application of light trapping in germanium thermophotovoltaic cells is very important in achieving high conversion efficiencies. An aluminium layer, together with an amorphous silicon passivation, gives a higher back surface reflection in combination with a good back surface passivation. Contact is formed through laser fired contacts.

An AM1.5 cell efficiency of 6.3 percent has been achieved, with a short circuit current density ($J_{sc}$) of 44.5 mA·cm$^{-2}$, a open circuit voltage ($V_{oc}$) of 243.1 mV and a fill-factor (FF) of 58.5 percent. Comparing the spectral response to a classical solar cell with a diffused aluminium BSF, an increased response at high wavelengths has been observed.

Further research will be done to test the cell performance under a TPV spectrum emitted by a heat source. Mainly the performance of the front- and back contact under high light intensities is of main interest. Also a further optimalisation of the laser fired contacts will be done, where the realisation of a dotted pattern is one of objectives.

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The cells were measured against a reference cell which is calibrated (traceable) to the World Radiometric Reference by the European Solar Test Installation (ESTI) of the European Commission Joint Research Centre, an ISO 17025 accredited calibration laboratory.

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