

## Dopant-free electron heterocontacts for silicon solar cells

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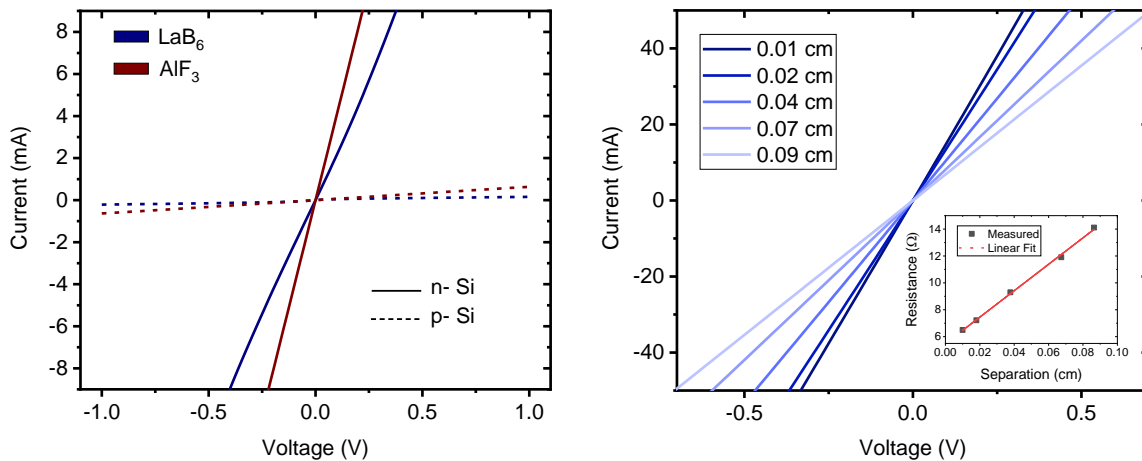
In the last decade, there has been an ongoing trend in the PV community towards the employment of passivated contacts in silicon solar cells. This trend is driven by the interest in approaching the 29.2% limit efficiency for silicon. In fact, some of the major PV companies have already started mass-scale production of solar cells featuring passivated contacts [1, 2]. However, the only passivated contact technologies that could catch the interest from industry so far are the polycrystalline and amorphous silicon-based. Typical solar cell structures implementing these layers are the Tunnel Oxide Passivated Contact (TOPCon) and the Silicon Heterojunction (SHJ) solar cells. The latter holds the silicon solar cell record efficiency of 26.7% [3]. Even though the passivating and electrical properties of these Si-based layers are excellent for both n- and p-type substrates, they present non-negligible absorption losses, especially when used at the front side of solar cells. In the case of poly-silicon contacts, an extra step for high temperature diffusion and activation of dopants is still required. On the other hand, a-Si layers typically suffer from low thermal stability. Aiming to tackle some of the disadvantages which are inherent to Si-based films, there is emerging research on the so-called “dopant-free” passivated contacts. As the name implies, these do not rely on doped silicon. Whereas silicon passivated contacts use doping to create carrier concentration asymmetry and achieve selectivity, most of these “dopant-free” materials make use of a suitable work-function difference or band alignment with the silicon substrate to create accumulation of either electrons or holes. Some transition metal oxides (TMO), such as  $\text{TiO}_x$  and  $\text{MoO}_x$  have been proven as potential electron and hole selective contacts, respectively. A solar cell architecture combining both TMO selective layers (at the front and rear sides) in a full-area configuration has been recently demonstrated, showing a power conversion efficiency above 23% [4].

The work described in the present abstract will focus on two prospective electron selective materials, namely aluminium fluoride ( $\text{AlF}_3$ ) and lanthanum hexaboride ( $\text{LaB}_6$ ). Such selective layers could be potentially employed as Partial Rear Contacts (PRC) or full-area passivating contacts in a solar cell. Some metal halides such as  $\text{LiF}_x$  and  $\text{MgF}_x$  are known to have a low work-function when stacked with aluminium and their excellent performance as electron contacts for silicon solar cells has been explored in the past [5, 6]. The  $\text{AlF}_3/\text{Al}$  system is expected to have a similar behaviour. Some years ago, aluminium fluoride drew interest as a passivating layer for p-type silicon when it was observed that fluorine vacancies at the  $\text{AlF}_3/\text{Si}$  interface could form negative fixed charges [7]. Lanthanum hexaboride is well known as a thermoionic emitter, and it is precisely its low work-function, in addition to its good stability, which suggests it as a good candidate for electron collection. In fact,  $\text{LaB}_6$  has been used in the field of organic photovoltaics as an electron injector at the donor side of the organic device. Besides improving the conversion efficiency, it enhanced the thermal aging of the solar cell [8]. To the best of the authors’ knowledge, neither  $\text{AlF}_3$  nor  $\text{LaB}_6$  have been studied as electron-selective contacts for Si solar cells.

The substrates used in this study were cleaved from 2  $\Omega$ -cm unpolished float zone n-type wafers, and received a HF dip prior to deposition. The precursors were anhydrous  $\text{AlF}_3$ , 99+% from Alfa Aesar;  $\text{LaB}_6$ , 99.9% from Fuzhou Yingfeixun Optoelectronic Technology, Co., Ltd.; and Al pellets from Angstrom Engineering. The  $\text{AlF}_3$  and Al films were thermally evaporated at a pressure close to  $10^{-6}$  mbar and rates  $<0.5$   $\text{\AA}/\text{s}$  and  $>4$   $\text{\AA}/\text{s}$ , respectively. Due to the high sublimation temperature of  $\text{LaB}_6$ , it was e-beam evaporated at the same pressure and using a rate around 0.1  $\text{\AA}/\text{s}$ . The specific contact resistivity ( $\rho_c$ ) was extracted using the Transfer Length Method (TLM). The TLM pattern was defined with a shadow mask and the resulting strips were isolated along the edges to minimize current spreading.

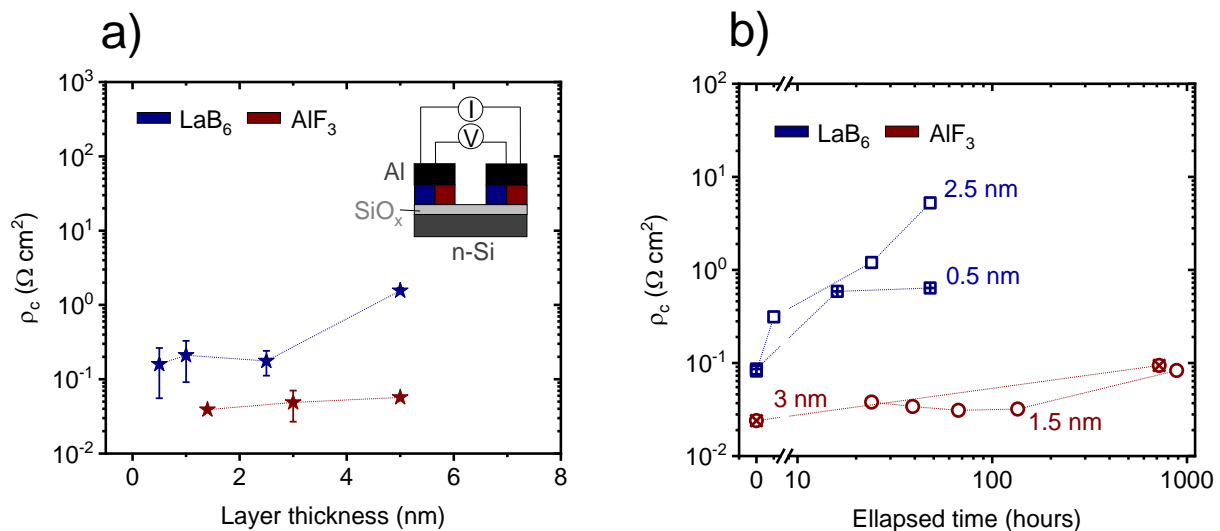
a)

b)



**Figure 1. a) Representative I-V curves for AlF<sub>3</sub> (1.4 nm) and LaB<sub>6</sub> (1.7 nm) comparing the behaviour in 2 Ω-cm n- and p- type silicon substrates. b) Set of I-V curves for a 1.4 nm thick AlF<sub>3</sub> film, for each TLM gap distance. The inset shows the resistance fit.**

As depicted in figure 1.a, the current extracted from the stacks is at least an order of magnitude lower when using a p-type substrate (with similar resistivity), proving their preference for electron collection. Figure 1.b displays representative I-V curves for different contact separations. The inset shows the TLM plot from which the specific contact resistivity was extracted by performing a linear fit of the resistance versus the gap distances. Figure 2 shows some preliminary results regarding the electrical properties and stability of LaB<sub>6</sub> and AlF<sub>3</sub>. Specific contact resistivities as low as 40 mΩ cm<sup>2</sup> can be achieved when using 1.4 nm of aluminium fluoride in between n-Si and aluminium. In the case of the c-Si/LaB<sub>6</sub>/Al stack, the contact resistivities are higher. Stability-wise, LaB<sub>6</sub> films suffer from an order of magnitude increased  $\rho_c$  already after 24 hours in air. Degradation is observed for 0.5 and 2.5 nm films likewise. On the other hand, the c-Si/AlF<sub>3</sub>/Al system displays good stability for both a 1.4 and 3 nm thick AlF<sub>3</sub> films in the studied timeframe (approaching 1000 hours).



**Figure 2. a) Specific contact resistivities measured using the Transfer Length Method as a function of film thickness, b) Specific contact resistivities of material layers with various thicknesses as a function of their time exposed to air atmosphere.**

In the next stage, this work will report the behaviour of these materials when combined with other layers such as  $\text{TiO}_x$  and  $\text{AlO}_x$ . Additionally, the passivation properties of the stacks will be investigated. Finally, the effect of annealing on the films will be assessed by evaluating the contact resistivity and charge carrier lifetime evolution with temperature.

## **References**

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