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Keywords:	Vertical solar cells, Intrinsic semiconductors, Micro-scaling, Concentrator photovoltaics, Ultra-high light intensities

Ultra-efficient intrinsic-Vertical-Tunnel-Junction (i-VTJ) structures for next-generation concentrator solar cells

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Highlights

- We propose a novel type solar cell that does not suffer the series resistance and band-gap optimization issues.
- Preliminary simulations have shown extreme efficiencies above 40% for GaAs/Si/Ge and GaAs/Si multi-bandgap configurations at light intensities of 10,000 suns.
- This early design offers a fast and reliable route to develop new generation ultra-efficient and low-cost concentrator photovoltaic systems.

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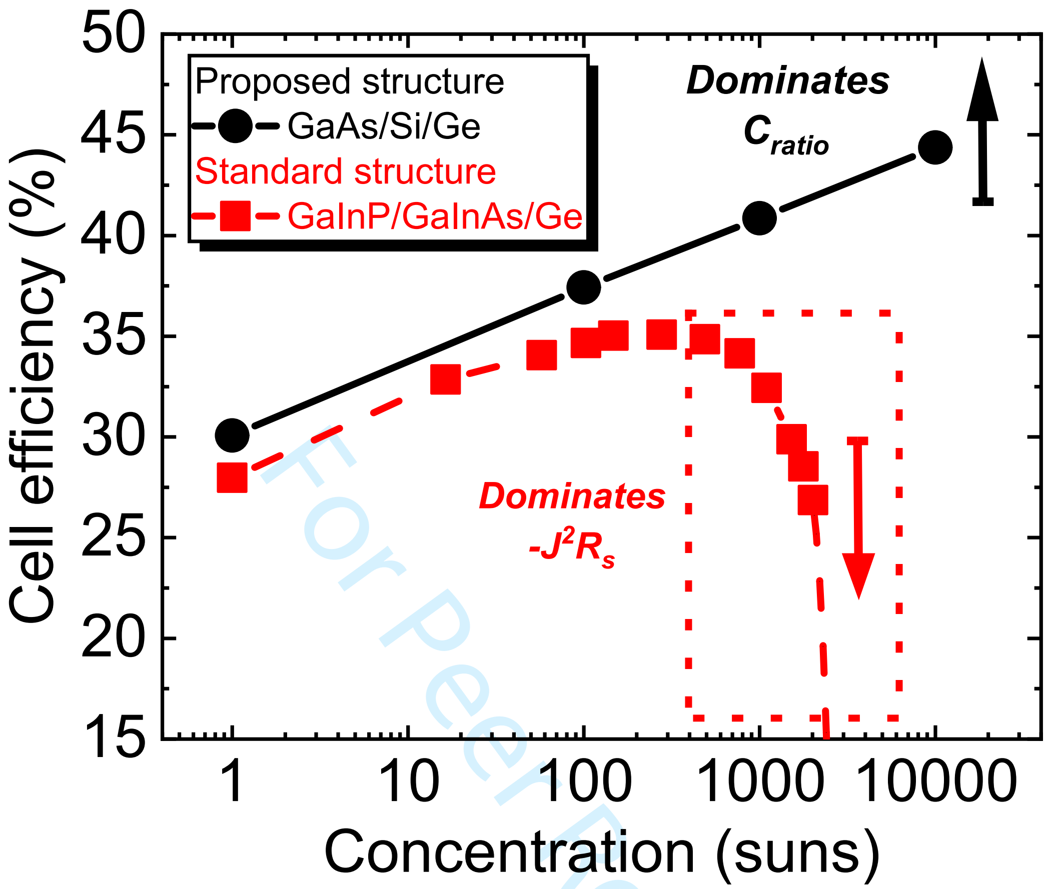

We propose a novel type of solar structure that does not suffer the resistance and band-gap optimization limitations of current concentrator solar cells. The new cell offers a unique route to achieve efficiencies far above the state-of-the-art, > 60%, and represent a promising way to push the efficiency towards the maximum conversion limit.

Abstract

The efficiency of solar cells can be enhanced by increasing the light intensity and/or the number of bandgaps of the structure. However, current solar cells cannot fully exploit these two factors due to various critical drawbacks. Here we show a novel micro-scale, i.e. side ≈< 0.5 mm, vertical solar cell structure that does not suffer the series resistance and band-gap limitations issues of current devices. The preliminary structures investigated show extreme efficiencies, > 40%, at ultra-high concentration factors of 10000 suns. In addition, future designs with a better band-gap configuration are expected to deliver cells with efficiencies far above 50% at extreme light intensities. This early design offers a fast and reliable route to push the efficiency towards the maximum solar conversion limit and represents a promising way to develop new generation ultra-efficient and low-cost concentrator photovoltaic systems.

Keywords Vertical solar cells, Intrinsic semiconductors, Micro-scaling, Concentrator photovoltaics, Ultra-high light intensities

1 Introduction

The efficiency (η) can be considered as the most important variable of any photovoltaic (PV) system. There are two direct ways to enhance its value: A) to concentrate the sunlight, i.e. the limit η of a single-band-gap cell is ≈ 30% at 1 sun, while it could reach ≈ 40% under fully concentrated sunlight, and B) to increase the number of band-gaps, i.e. the limit η of an infinite-band-gap cell is ≈ 65% at 1 sun. The exploitation of A) and B) can lead to next-generation solar devices with η > 80% [1].

Multi-junction (MJ) cells take advantage of these and have demonstrated impressive η > 40% for concentrations (C_{ratio}) within 100-1000 suns [2]. Nowadays, MJ cells mostly consist of monolithic structures made up of III-V semiconductors with different energy gaps [3]. The most critical limiting factor of these devices to enhance η with C_{ratio} is related to the huge increase of the series resistance (Rs) losses as the light intensity is increased [4]. This limitation is imposed by the trade-off between the shadowing of the front metallic contact and the Rs. In this sense, it has not been possible to develop cells with η peaking at C_{ratio} ≈> 1000 suns no matter how the front-grid pattern is designed or how much the area of the cell is reduced [5]. Hence, they cannot fully exploit the theoretical increase of η with C_{ratio}, and therefore completely leverage the cost reduction capacity of concentrator PV (CPV) systems [6].

Vertical-multi-junction (VMJ) solar cells are based on the series connection of multiple subcells with the metal contacts located on the lateral [7, 8]. This allows solar cells with low current densities and series resistance (Rs) values to be developed, and therefore, opens a promising way of eliminating the limitation of current MJ cells with C_{ratio}. However, the use of metallic contacts to connect each pn junction in the VMJ stack limits the semiconductor selection to indirect band-gap materials, i.e. high diffusion lengths (L) L≈ 100-300 μm are needed due to manufacturing issues [9, 10]. Therefore, the bang-gap selection is limited, and they present a critical drawback for developing high-efficiency multi-bandgap (MBG) structures with an optimum exploitation of the spectrum [11].

In this work, we propose a novel ultra-efficient micro-scale vertical structure of solar cell that does not suffer the Rs and band-gap optimization limitations. Its fundamental design is based on the vertical-tunnel-junction (VTJ) solar cell recently introduced by the authors [12]. The new device will result in a step-change in performance of our previous design and will allow next-generation concentrator cells operating at ultra-high C_{ratio} with an ideal exploitation of the spectrum to be developed.

Taking the above into account, the novel design offers a unique way for developing the so-called ultra-high concentrator photovoltaic (UHCPV) systems, i.e. C_{ratio} > 2000 suns [13]. These systems are currently recognised as one of the most promising research avenues in producing a new generation high-efficiency and low-cost PV technology [4, 5, 14-16]. In this sense, the novel solar cell architecture is expected to accelerate new developments towards ultra-efficient competitive CPV systems.

This work is intended to investigate the potential of a new type of vertical solar cell architecture by performing detailed simulations. In this sense, this communication represents a first step that is expected to serve as proof of concept of next-generation ultra-efficient concentrator solar cell.

2 Device structure and Simulation

Figure 1 shows the basic layout of the so-called intrinsic-Vertical-Tunnel-Junction (i-VTJ) solar cell. The proposed structure is made up of two identical subcells connected in series by using a highly doped tunnel junction (TJ) with a negligible Rs, i.e. 10^{-5} to 10^{-7} $\Omega\cdot cm^2$ [17]. As in our previous design, the i-VTJ cell overcomes the trade-off between the shadowing of the front metal-grid and Rs of current MJ cells. The area of the lateral metallic contacts can be increased without restriction and the Rs limitations eliminated, i.e. Rs is reduced by a factor ≈> 10^2. Furthermore, the tunnelling connection allows both indirect and direct band-gap semiconductors with low L to be selected. This is fundamental for the bandgap engineering of MBG structures tailored to achieve efficiencies beyond the current state-of-the-art. This single-band-gap architecture represents the fundamental unit to produce the novel MBG cell also introduced in this work.

The key innovation of the i-VTJ compared with our previous design is that an intrinsic semiconductor layer (i-layer) is included between the pn junctions. This reduces the recombination rate since L is higher in intrinsic semiconductors. Moreover, the electric field responsible for charge carrier separation covers most of the illumination area of the structure. In this way, the photon collection, and therefore η, can be enhanced. In addition, the i-layer allows the width (W) to be increased and the number of TJs to be drastically reduced for designs with higher areas based on the tunnelling connection of multiple i-VTJs. This is key to diminishing the processing time and possible strain effects in the TJs, and therefore, to facilitate the fabrication of the device. It is worth mentioning that micro-scale solar cells with sides ≈< 0.5 mm are desirable. This is important since the micro-scaling of CPV is key to achieve UH C_{ratio}, i.e. it facilitates the thermal management and reduce the cell-to-module losses of real case CPV systems [18, 19].

It is worth mentioning that, at this stage, i-VTJ cells only made from one material have been considered. Furthermore, additional layers such as optically coupled anti-reflective coatings (ARC), aimed at diminishing the reflective losses and increasing the photon absorption, are not considered. The intention is to propose an architecture as simple as possible to facilitate future work concerning its manufacturing. However, these should be also investigated to further enhance the efficiency of the device.

The proposed structure has been investigated by using the Silvaco ATLAS software [31]. This software solves the Poisson and transport equations under the correct boundary conditions in all the layers of the device. Silvaco ATLAS is a widely used simulation suite that has proven to deliver trustable results for designing electronic devices, including MJ concentrator solar cells [32]. In this communication, i-VTJ solar cells made up of GaAs, Ge and Si have been considered in the simulations. This allows reliable results to be obtained since their physical properties have been extensively investigated. Also, they permit a preliminary study towards obtaining MBG i-VTJ solar cells to be conducted. As a first step in the design, concentrator standard test conditions (CSTC) have been considered in all the simulations, i.e. AM1.5d, 1 sun = 1000 W/m^2 and 25 °C.

3 Results and Discussion

Figure 2 shows the efficiency of the three solar cells considered as a function of the thickness of the i-layer for various C_{ratio}. As can be seen, this layer increases the feasibility in the design and allows high-efficiency i-VTJ cells with a larger W than state-of-the-art vertical structures to be developed. Our previous VTJ cell design based on GaAs [12], the only vertical cell made up of this material at the present, showed a η ranging from ≈23% at 1 sun to ≈28% at 10,000 suns for a W ≈ 10 μm. This means that the W of the GaAs i-VTJ cell can be increased from more than 20 times at 1 sun (i-layer ≈ 100 μm) to around 4 times (i-layer ≈ 20 μm) at 10,000 suns to reach similar efficiencies. In this figure, a reduction in the optimal thickness range as the C_{ratio} grows can be also seen. This is due to the fact that the lifetime (τ) of the carriers decreases with the injection level due to radiative and auger recombination mechanisms [20].

The thickness of the i-layer shows a higher flexibility for the Si and Ge i-VTJ cells and allows W to be strongly enlarged. This can be understood by considering that they are indirect band-gap materials with a τ on the i-layer more than 10^{-2} s larger than that of the i-VTJ GaAs direct band-bap cell [21, 22]. The comparison of the increase of W due to the introduction of the i-layer with previous designs is not direct since there were no VTJs cells made up of these materials prior to this work. The most appropriate approach seems to be to compare half the W of the new cell with VMJs. This can be explained by the fact that the latter does not include a TJ to connect two identical subcells. In this sense, Si VMJ cells usually show an optimum subcell W < 120 µm at a C_{ratio} = 1 sun [9]. As can be seen in Fig. 2, the Si i-VTJ could reach thickness of around 1200 µm without any degradation in η, a W approximately 10 times larger. This is even enhanced in the Ge i-VTJ, which shows W up to 2000 µm without drastically affecting η for all the C_{ratio} here investigated.

Figure 3 shows the efficiency as a function of the C_{ratio} for the three materials investigated. The dimensions of the different layers are listed in Table 1. The ultimate intention of this work is to introduce high-efficiency solar cells suitable for achieving ultra-high concentration levels. Bearing this in mind, i-VTJ cells optimized to reach the maximum η at 10,000 suns have been considered in these simulations. In any case, it should be pointed out that, there will be several trade-offs in the optimization as a function of the C_{ratio} or the minimum W imposed by manufacturing constraints for each particular case. As can be seen in the figure, η grows linearly with the logarithmic increase of light intensity. The introduction of the i-layer allows the efficiency to be increased beyond the state-of-the-art vertical configurations. The GaAs i-VTJ cell reach a maximum η = 33.8%, an increase of around 5% compare with our previous VTJ design. In addition, this would represent a record efficiency cell, it is 29.3% for a single-band gap cell at C_{ratio} ≈ 50 suns [23]), and offer a promising way to reach η > 30% by using single-junction solar cells. Also, the Si and Ge i-VTJ cells achieve high efficiencies exceeding 20% for concentrations above 1000 suns. The simulations indicate that the i-VTJ cells investigated do no suffer either Rs. Also, no other limitations such as Auger recombination have been found. The latter is also relevant considering that this mechanism is signalled as a key limiting factor of solar cell with C_{ratio} [24], especially in indirect band-gap materials such as Si and Ge due to the extreme amount of phonons available [20].

The i-VTJ structure opens the way to the use of either direct or indirect band-gap materials. In this way, it is possible to select the appropriate energy gaps as a function of the number of band-gaps considered. Figure 4 shows a scheme of a 3BG i-VTJ made up of GaAs/Si/Ge as a proof of concept. This mechanically stacked structure would avoid the lattice-matched restrictions. Hence, the band-gap optimization is more flexible than in current MJ cells. In addition, since the power of each cell is independently extracted, the device eliminates the current-matching restrictions. This is fundamental in reducing the outdoor spectral losses, which reduce the practical η of current devices around 5% [25], and seems to prevent the development of MJ cells with more than five band-gaps [26].

Figure 3 also shows η versus C_{ratio} for the 3BG i-VTJ cell, as well as for a 2BG configuration made up of GaAs/Ge. As can be seen, both devices achieve outstanding η exceeding 40%, similar to the best MJ cells nowadays, but at a C_{ratio} one of magnitude higher. Indeed, the 2BG cell presents a peak η around 5% higher than the record double-junction cell nowadays, i.e. η = 35.5% at a C_{ratio} = 381 suns [23]. The energy gap of the materials here considered, i.e. 1.42 eV (GaAs), 1.08 eV (Si) and 0.66 eV (Ge), is far from the optimum to maximize the absorption of the spectrum. The optimal 3BG configuration should be 1.75 eV (top), 1.18 eV (middle) and 0.7 eV (bottom), while it should be 1.57 eV (top), 0.94 eV (bottom) for the 2BG case [26]. In this sense, the η achieved should be considered as a first step of the real potential. Materials such as GaInP, GaInAs or GaInAsP could be used to get alloys with energy gaps ranging from 0.4 to 2.3 eV [27]. Hence, it seems feasible to develop MBG i-VTJ cells with six or more band-gaps, which shows theoretical η ≈ 60% at 1 sun [26]. Bearing this in mind, future designs are expected to deliver η > 60% for designs with a number of band-gaps beyond current developments.

The manufacturing of the architectures discussed is outside of the scope of this work. Despite this, further comments regarding this topic are of interest to give evidence about its feasibility. For instance, the i-VTJ cell could be epitaxially-grown by connecting multiple TJs in series. This seems feasible considering the high accuracy of the manufacturing techniques nowadays, the micro-scaling, i.e. cell sides ≈< 0.5 mm, as well as the fact that the viability of monochromatic PV power converters with 20 pn junctions have already been proven [28]. In addition, the metallic contacts can be placed on the laterals of the structure using well-known techniques since the total W is similar to the thickness of current MJ cells, which is around ≈ 0.2 mm [29]. Once each i-VTJ device is available, the final MBG-i-VTJ could be manufactured by mechanically stacking each i-VTJ. This is also supported by the latest techniques to produce mechanically staked cells, such as transfer-printing, which has shown reliable results to develop micro-scale triple-junction MJ cells with η ≈ 45% at a C_{ratio} ≈ 840 suns [30]. This architecture is expected to have a higher cost than current MJ solar cells. However, as previously investigated by the authors, at such C_{ratio} the cost of the cells remains marginal even if the cost of the chip would be double than those currently produced [6, 12].

4 Conclusions

We have proposed a novel ultra-efficient micro-scale vertical cell suitable for achieving ultra-high concentrations (C_{ratio}), i.e. C_{ratio} > 2000 suns. The so-called intrinsic-Vertical-Tunnel-Junction (i-VTJ) introduces a i-layer between the pn junctions as a key innovation. Also, it takes advance of a recent design of the authors based on the use of tunnel junctions (TJ) to connect multiple vertical subcells. The i-VTJ is investigated by performing simulations using TCAD software for three materials, i.e. GaAs, Si and Ge, up to 10,000 suns. The i-layer improves the photon collection and allows record efficiencies (η), e.g. η > 30% for a GaAs i-VTJ at C_{ratio} ≈> 1000 suns, to be achieved. Moreover, the i-layer increases the flexibility in the design and permits the width of the structure to be reduced. This is key to limiting the number of TJs and to facilitate the manufacturing of the device. Indeed, it would be possible to develop high-efficiency GaAs cells with TJ ≈< 20, Si with TJ ≈< 5 and even Ge without TJs for the targeted areas, i.e. ≈< 0.5 x 0.5 mm^2.

The i-VTJ can be made up of direct and indirect band-gap materials. This permits the achievement of an ideal exploitation of the spectrum without series resistance limitations. Preliminary simulations have shown extreme η > 40% for GaAs/Si/Ge and GaAs/Si multi-bandgap (MBG) configurations at a C_{ratio} = 10,000 suns. Future designs with a better MBG configuration are expected to deliver cells with η > 60%. This work is intended to serve as a proof of concept of a new vertical solar cell configuration. Based on this, the authors plan to fabricate and characterize various prototypes to give more evidences of the potential of the new solar cell device.

Acknowledgments

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Table and Figure Captions

Table 1 Dimensions of the i-VTJ solar cells considered for a concentration of 10,000 suns.

Fig. 1. Scheme of the i-VTJ solar cell (H = height and W = width).

Fig. 2. Width of the intrinsic layer versus the efficiency and sun concentration for the i-VTJ solar cells considered.

Fig. 3. Efficiency versus concentration for the GaAs, Si and Ge, and the MBG GaAs/Si/Ge and GaAs/Si, i-VTJ solar cells optimized for a concentration of 10,000 suns.

Fig. 4. Scheme, not to scale, of the simulated 3BG i-VTJ solar cell for a concentration of 10,000 suns. Note that the Germanium´s width is approximately half the optimum W shown in Table 1 since it does not need a TJ for this particular design.

Table 1

Material Dimension (μm)	GaAs	Si	Ge
P+ layer	0.06	0.5	1.8
P layer	0.05	16.0	1.0
Intrinsic layer	9.78	23.0	410
n layer	0.07	0.9	1.0
n+ layer	0.01	0.1	3.0
Total height (H)	5	295	265
Total width (W)	20	81	834

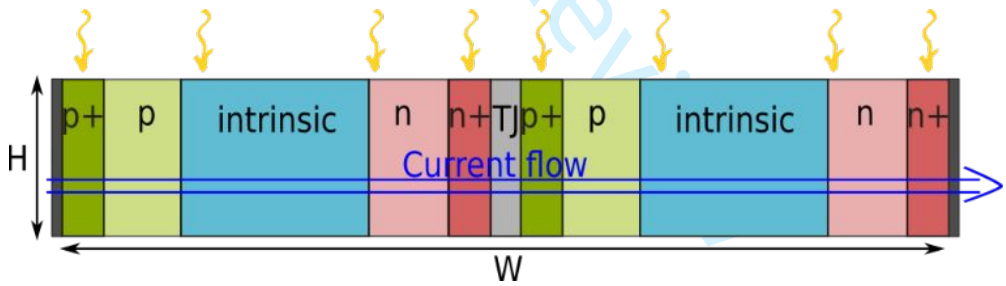
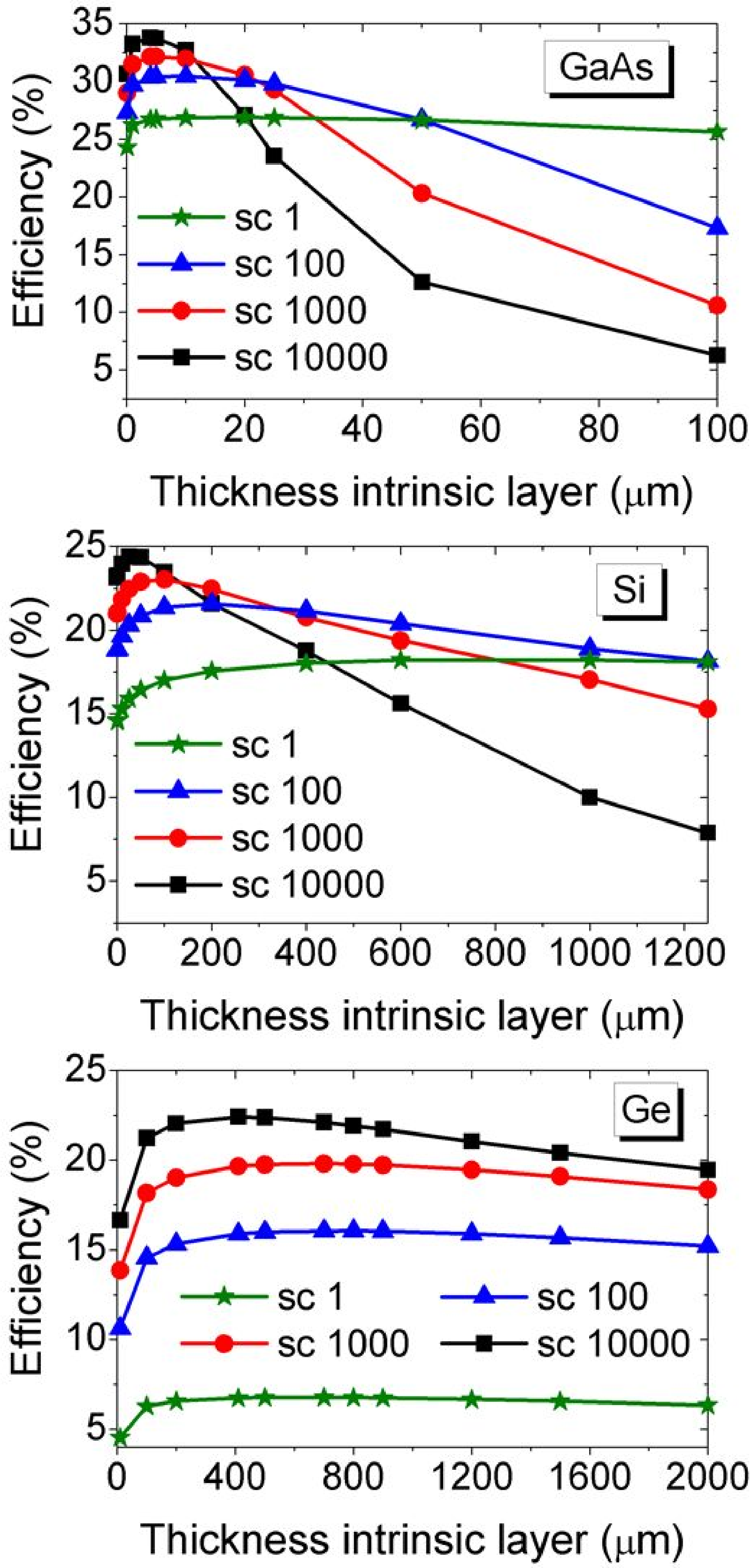


Fig. 1.


GaAs
Efficiency (%)
sc 1
sc 100
sc 1000
sc 10000
Thickness intrinsic layer (μm)
Si
Efficiency (%)
sc 1
sc 100
sc 1000
sc 10000
Thickness intrinsic layer (μm)
Ge
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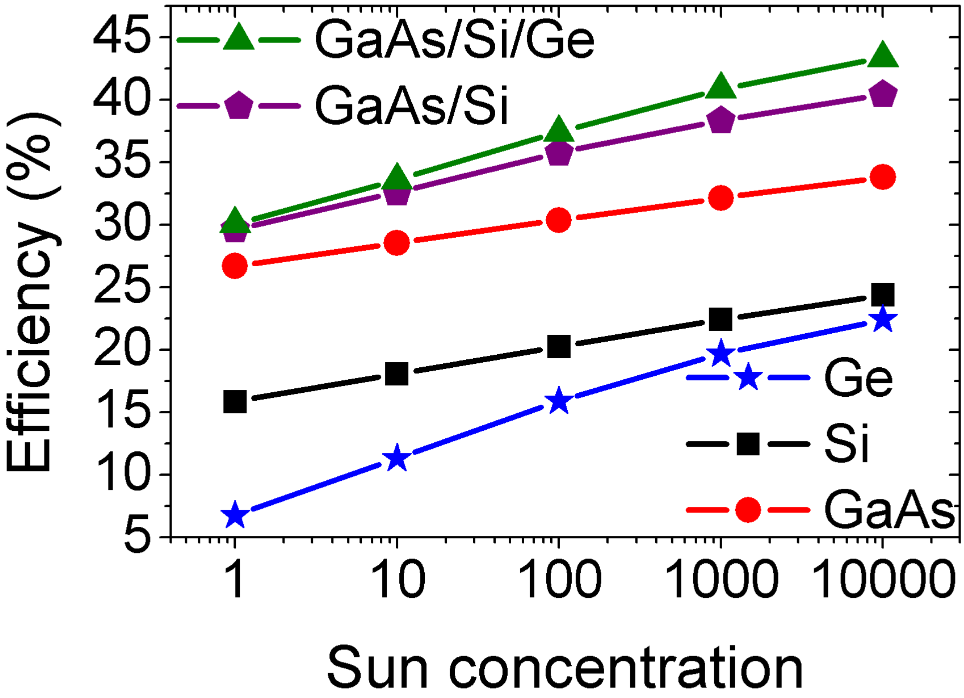
sc 1
sc 100
sc 1000
sc 10000
Thickness intrinsic layer (μm)

Fig. 2.



GaAs/Si/Ge
GaAs/Si
Ge
Si
GaAs
Efficiency (%)
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40
35
30
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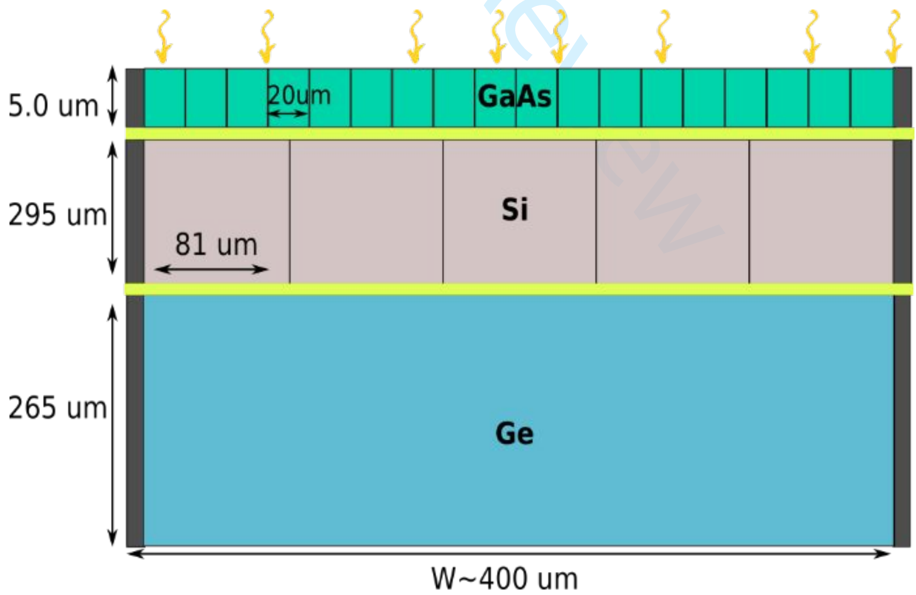
10
5
1
10
100
1000
10000
Sun concentration

Fig. 3.



5.0 um
20um
GaAs
295 um
81 um
Si
265 um
Ge
W~400 um

Fig. 4.