Flexible solar cells based on stacked crystalline semiconductor nanomembranes on plastic substrates

Weiquan Yang[1], Weidong Zhou[1], Zhenqiang Ma[2], Jesper Berggren[3], and Mattias Hammar[3]

[1]NanoFAB Center, Department of Electrical Engineering, University of Texas at Arlington, Arlington, TX 76019, USA (wzhou@uta.edu)
[2]Department of Electrical and Computer Engineering, University of Wisconsin-Madison, WI 53706, USA
[3]School of Infrmation and communication technology (ICT), Royal Institute of Technology (KTH), SE 164 40, Kista, Sweden

Abstract: We report here experimental demonstration of flexible solar cells based on crystalline semiconductor nanomembranes (NMs) transferred onto flexible PET (polyethylene terephthalate) substrates. For 1 micrometer thick p-i-n InP NMs, we obtained an open circuit voltage of 0.68 V and power efficiency of 1.5% from the photovoltaic solar cells. The results agree very well with the anticipated thin film InP solar cell performance considering the low absorption in very thin InP NMs. The efficiency remains unchanged for bending radii greater than 42 mm. It drops to 50% of its original value at a bending radius of 32 mm. The results demonstrate a promising future for such a new type of cost effective flexible thin film solar cells, based on *crystalline* semiconductor membranes.

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Thin film solar cells based on high quality single crystalline semiconductors, with combined high performance and low material consumption, offer one of the most promising approaches for cost competitive electricity generation,.[1] Recently, a disruptive low temperature transfer process has been developed by Ma *et. al*, with which single crystalline semiconductor nanomembranes (NMs) can be transferred to foreign substrates for high performance flexible electronic and photonic devices.[2-6] We report here experimental demonstration of large area flexible solar cells based on III-V crystalline semiconductor NMs transferred onto flexible PET (polyethylene terephthalate) substrates. We address two critical challenging issues related to large-area thin film solar cells. The first one is reliable and manufacturable transfer of large-area crystalline semiconductor NMs, especially for fragile materials systems (e.g. InP). The second challenge is the effective incorporation of metal contacts for the desired electrical properties of photonic devices. We developed a frame-assisted membrane transfer (FAMT) process to address these challenges, with the demonstration of high efficiency flexible thin film solar cells.

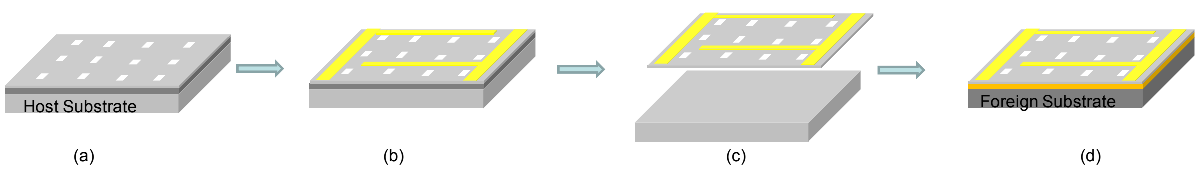

Fig. 1 Process flow of a metal frame-assisted membrane transfer (FAMT) process for large area crystalline semiconductor nanomembrane transfer: (a) Formation of release holes on the top membrane layer; (b) Formation of metal frames, serving as the electrical contacts as well as the supporting frames; (c) Release of top membrane layer by selective etching of sacrificial layer between the top membrane layer and the host substrate (e.g. SiO_2 in SOI structure, InGaAs in InP structure); and (d) transfer of top membrane to a foreign substrate (e.g. glass, flexible PET substrates).

Flexible InP p-i-n solar cells were formed on a PET substrate, based on the FAMT process shown schematically in Fig. 1. The starting material is a vertical p-i-n InP top membrane layer (total thickness of 1 μm) grown on top of an InP substrate, with an InGaAs sacrificial layer sandwiched in between. Release holes were formed first on the top InP layer (Fig. 1(a)), followed by Au finger-type contact formation (Fig. 1(b)). The Au finger contacts here also provide the desired mechanical strength for the successful transfer of the large area InP NMs. Top pin InP membrane layer was subsequently released from the host InP substrate, by selective etching away the InGaAs sacrificial layer (Fig. 1(c)). Finally, the InP membrane layer was

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transferred to a flexible ITO/PET substrate (Fig. 1(d)). Shown in Fig. 2(a) and 2(b) are the schematics of crystalline thin film solar cells on the flexible PET substrate, with top Au finger electrical contacts and bottom ITO transparent contacts. Shown in Fig. 2(c) and Fig. 2(d) are the pictures and micro-graphs of the fabricated flexible InP solar cells on the ITO/PET substrate. Very high quality 3 mm x 3 mm InP NMs were successfully transferred. Membranes of larger than this size for practical use can also be transferred.

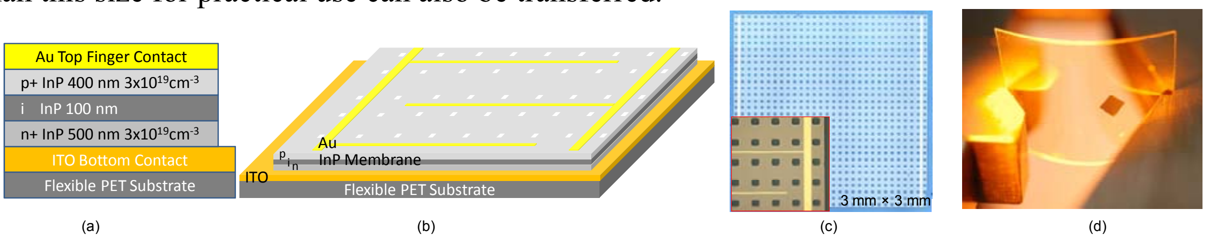

Fig. 2 (a, b) Schematics of a InP p-i-n solar cell, based on transferred crystalline semiconductor nanomembrane processes; (c) A micrograph of a fabricated large area (3x3 mm^2) InP solar cells on flexible PET substrate, with inset shown the zoom-in view of top finger contact; and (d) A close-up image of a fabricated crystalline flexible thin film solar cell on a bent PET substrate.

The measured current-voltage curve for the flexible InP solar cell without bending under dark condition is shown in Fig. 3(a), with dark current less than 1 μA. For 1 micrometer thick p-i-n InP NMs, we obtained an open circuit voltage of 0.68 V and power efficiency of 1.5% from the photovoltaic solar cells, as shown in Fig. 3(b). The results agree very well with the anticipated thin film InP solar cell performance considering the low absorption in very thin InP NMs (no intentional antireflection was used). Higher efficiency cells are feasible with optimized structural design by optimal absorption, light trapping, and photon recycling. The measured bending performance is shown in Fig. 2 (b). The efficiency remains unchanged for bending radius greater than 42 mm, but drops to 50% of its original value at a bending radius of 32 mm.

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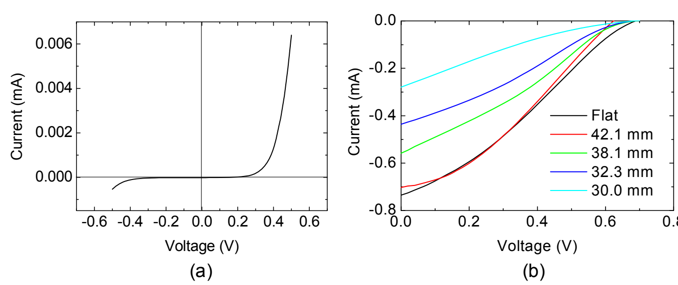

Fig. 3 Measured flexible crystalline InP thin film solar cell characteristics: (a) Dark current; and (b) Currents at different bending radii, under standard AM solar simulator test conditions at room temperature.

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