

Transfer-printed Electrodes for Colloidal Nanocrystal Solar Cells Utilizing “Soft” Polydimethylsiloxane Stamps

Sarah Swisher



Electrical Engineering and Computer Sciences
University of California at Berkeley

Technical Report No. UCB/EECS-2012-45

<http://www.eecs.berkeley.edu/Pubs/TechRpts/2012/EECS-2012-45.html>

April 25, 2012

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Transfer-printed Electrodes for Colloidal Nanocrystal Solar Cells Utilizing “Soft” Polydimethylsiloxane Stamps

by Sarah Lohry Swisher

Research Project

Submitted to the Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, in partial satisfaction of the requirements for the degree of **Master of Science, Plan II**.

May 11, 2012

Approval for the Report and Comprehensive Examination:

Committee:

Professor A. Paul Alivisatos
Research Advisor

(Date)

* * * * *

Professor Vivek Subramanian
Second Reader

(Date)

Abstract

Over the past decade, colloidal nanocrystal solar cells have been increasingly investigated as a candidate for low-cost, solution-processed photovoltaics. While colloidal nanocrystals have the potential to combine the superior optical and electrical properties of inorganic semiconductors with the ability for inexpensive, large-area solution-processing manufacturing techniques, significant challenges exist that have limited the performance of devices thus far. One of the most crucial issues yet to be solved is the formation of high-quality Ohmic contacts to the photoactive material that does not damage the nanocrystal film.

Many novel thin film device architectures would benefit from a reproducible method of depositing metal electrodes using a non-damaging technique that is compatible with low-temperature processing requirements. Thermal evaporation of metal electrodes onto thin films of semiconductor nanocrystals can result in damage to the crystal surfaces, diffusion of the metal into the nanocrystals, and shorting of the device through pin-holes in the nanocrystal film. Here we present an alternative method for electrically contacting semiconductor nanocrystal thin films using elastomeric stamps, where transfer of the metal to the substrate does not require an interfacial adhesion layer. We have demonstrated the usefulness of this contact method using a well-studied system of lead chalcogenide quantum dots. The elastomeric stamp contact deposition method not only allows reproducible contacts to materials prone to pin-holes, but also enables thinner layers of active material, which could benefit thin film solar cells that suffer from a short carrier mean free path.

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Introduction

Motivation: The Clean Energy Challenge

There is arguably no greater challenge facing the scientific community than developing energy technologies that are environmentally benign, efficient, reliable, and cost-effective. The ill effects of our global dependence on coal and oil – with regards to the environment, political stability, and the world economy – are becoming increasingly apparent. Establishing new global energy systems that utilize clean, renewable energy is of vital importance. Solar radiation is the most abundant form of energy on Earth; more energy from the sun strikes the surface of the Earth in one hour (4.3×10^{20} J) than the entire planet consumes in a year (4.1×10^{20} J), yet it provides less than 0.1% of the world's electricity.¹ There is enormous untapped potential in our solar resource, but incremental increases in photovoltaic (PV) efficiency will not enable solar energy to fulfill its potential. We need *revolutionary*, not evolutionary, discoveries to drastically reduce the cost per watt, and allow new PV technology to permeate the market. Light interacts with materials on the order of its wavelength (a few hundred nanometers), so controlling matter on this length scale could potentially lead to dramatic improvements in the efficiency of capturing solar energy.

Colloidal Nanocrystal Solar Cells

The recent advancement of nanotechnology has shown great promise for disruptive discoveries regarding our ability to harvest solar energy in the near future. In particular, colloidal semiconductor nanocrystals have been an area of intense focus because they combine the superior optical and electrical properties of inorganic semiconductors with the ability for inexpensive, large-area solution-processing manufacturing techniques. In many materials, the strong quantum confinement in colloidal nanocrystals allows their bandgap and absorption edge to be tuned across the entire visible spectrum,^{2, 3} providing unprecedented control over material properties that may enable a new class of photovoltaic devices.

Early demonstrations of nanocrystal solar cells were hybrid organic-inorganic devices utilizing colloidal nanocrystals dispersed in polymers.⁴ All-inorganic nanocrystal solar cells were soon realized with a donor-acceptor bilayer device comprised of CdTe and CdSe nanocrystal layers.⁵ Since then, nanocrystal solar cells have become an area of intense research

interest, producing different architectures such as Schottky solar cells⁶ and depleted heterojunctions⁷ that have achieved overall power conversion efficiencies above 5%.

Despite the recent progress, there are many aspects of nanocrystal devices that need to be explored and understood before efficient nanocrystal solar cells can be realized on a commercial scale. These including the hopping of charge carriers between nanocrystals, the effects of ligand coverage on transport and passivation, and the air-stability of both the inorganic core and the organic ligand shell surrounding the nanocrystal. However, making reliable, non-damaging electrical contacts to the nanocrystals is a fundamental challenge that must be overcome before results from any electrical studies can be reliably interpreted.

Electrical Contacts for Nanocrystal Films

Existing Methods

The general scheme for fabricating a quantum dot (QD) solar cell is as follows. Glass substrates on the order of one square centimeter are coated with a patterned transparent conductor, typically ~100 nm of indium tin oxide (ITO). A thin film (100-200 nm) of quantum dots is deposited onto the ITO using a solution-processing technique such as dip-coating or spin-casting. The most straightforward solar cell structure is made by evaporating a metal contact, typically Aluminum, directly onto the nanocrystals to make a Schottky device: QDs deposited onto ITO form an Ohmic contact, and thermally evaporating metal electrodes forms the Schottky junction.^{6, 8} The metal electrodes are patterned by evaporating through a shadow mask, which avoids exposing the nanocrystals to the harsh lift-off steps required for lithographically defined contacts. Figure 1a shows the device schematic that is often drawn to illustrate nanocrystal devices, but unfortunately this picture is not always realistic. In reality, the quantum dot films are often rough and even discontinuous, resulting in shorts from the evaporated electrodes through the film to the ITO beneath as shown in Figure 1b. This is becoming an increasingly important challenge as we reduce the device thickness, which could be beneficial for device performance because it would 1) reduce the number of interparticle hops required for charge carriers to reach the electrodes, and 2) enable the utilization of a super-absorbing material with short carrier diffusion lengths, such as iron pyrite. In the extreme case of a monolayer of nanoparticles where

the film is only tens of nanometers thick, it is clear that evaporated electrodes will not produce reliable devices, and an alternative contacting method will be required.

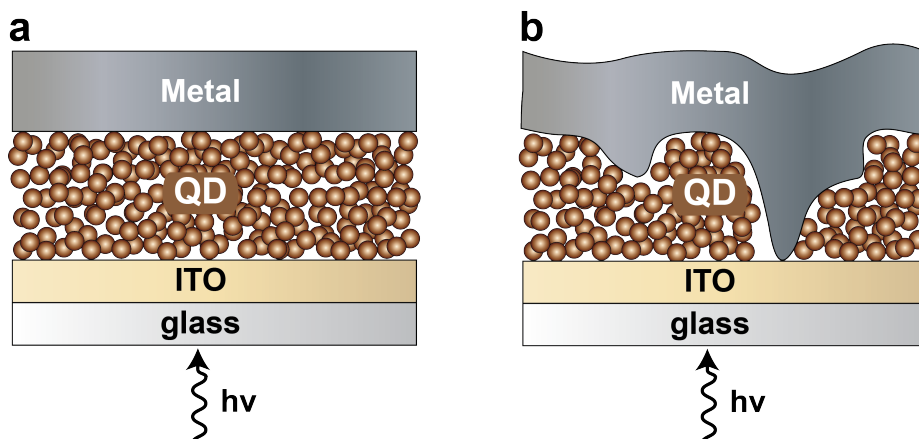


Figure 1. Schematic diagram showing the cross-section of a typical nanocrystal solar cell in an ideal case (a) and illustrating evaporated electrodes shorting through pinholes in the nanocrystal film (b).

The scanning electron microscope (SEM) images shown in Figure 2 illustrate well the challenge of contacting a very thin layer of nanocrystals. These images are taken looking down onto a film of vertically aligned rod-shaped nanocrystals on a glass/ITO substrate, successively zooming in from left to right.⁹ Aligned monolayers of nanorods have been investigated as a way to improve transport in nanocrystal solar cells, because they provide a nearly uninterrupted, single-crystalline path to the electrodes for charge collection.¹⁰ The roughness of the film is evident in Figure 2a, and the relatively large cracks are clearly visible. In Figure 2b, the cracks in the film of aligned nanorods expose the ITO surface below, where an evaporated electrode would create an electrical short through the device.

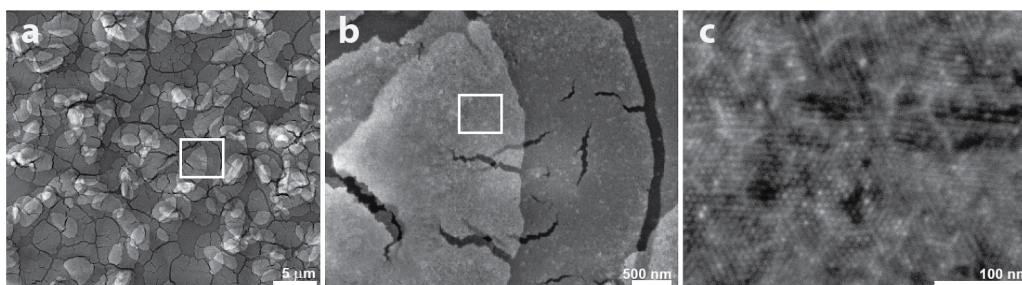


Figure 2. Scanning electron microscope (SEM) images taken looking down onto a film of vertically aligned nanorods, with progressive zoom from a to c. From Baker, *et al.*⁹

Even a continuous, crack-free nanocrystal film will be difficult to electrically contact without significantly altering the surface of the nanorods. Colloidal quantum dots and rods are

some of the most well-controlled quantum structures available, but this control comes at a price; the solution-based preparation and the complicated surface ligand chemistry means it is difficult to make reliable electrical contacts and reproducible measurements of these structures. The properties of the nanocrystals are closely tied to the surface conditions because of the high surface-to-volume ratio. Previous work by Trudeau *et al.* shows that evaporated contacts cause metal to diffuse into the nanoparticles, altering their electronic properties on length scales up to ~ 50 nm.¹¹ Thus if we want to make devices in which we are measuring the properties of the nanocrystals themselves and minimize the effect of the electrodes, an alternative method to make electrical contact is required.

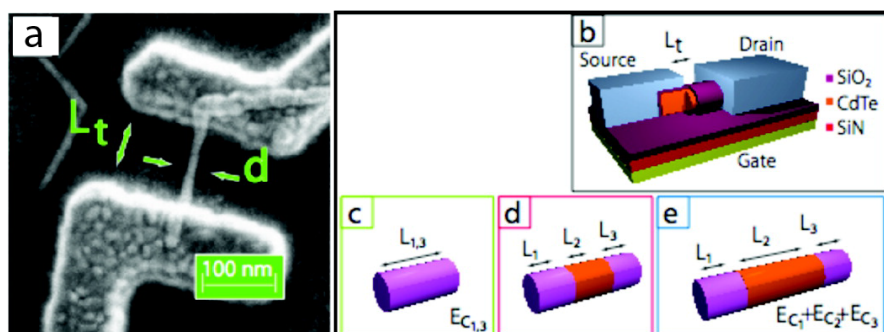


Figure 3. Evaporation of metal electrodes onto single nanocrystals causes diffusion of the metal into the nanocrystal, significantly altering its electronic properties. From Trudeau, *et al.*¹¹

Many groups have studied alternative methods for electrode deposition to avoid the complications of evaporated electrodes mentioned above. Zaumseil *et al.* developed an electrode lamination method utilizing an elastomer stamp, where the metal film remains attached to the elastomer stamp.¹² The metallized stamp is brought in contact with the device substrate for electrical measurements (Figure 4a). This method can successfully make contact to a very smooth organic semiconductor layer, but with a rough film of nanocrystals it would be difficult to make intimate contact between the electrodes and the semiconductor film.

Another option in the same vein is the nanotransfer printing method, which employs a self-assembled monolayer (SAM) of 3-mercaptopropyltrimethoxysilane (MPTMS) on a silicon wafer. A patterned elastomer stamp is coated with a thin film of gold, and brought into contact with the MPTMS-treated silicon. The exposed thiol groups of the SAM act as an interfacial “glue” layer that bind to the gold film and pull it off of the stamp.¹³ As seen in Figure 4b, this method can produce micron-scale patterns of gold on silicon wafers. However, the method is not well suited to stamping electrodes onto nanocrystal films: depositing a uniform SAM on the

rough film would be difficult, and the additional alkane chain would add to the already challenging surface ligand chemistry.

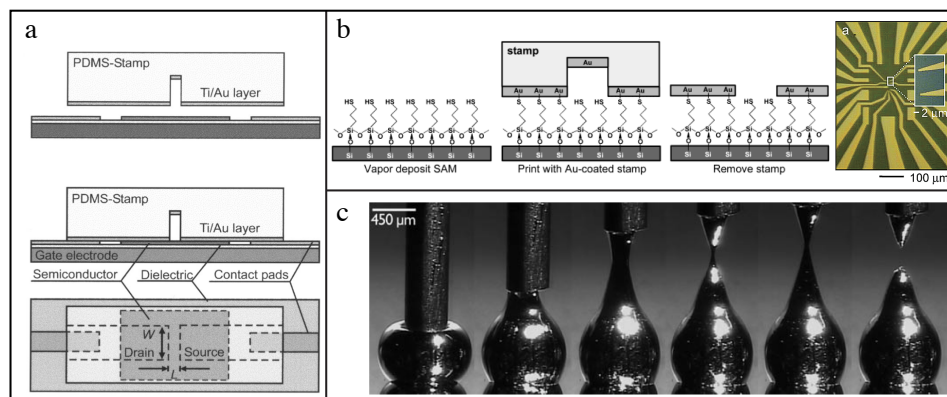


Figure 4. (a) Laminated contacts remain in contact with the device during testing. From Zaumseil, *et al.*¹² (b) Nanotransfer printing scheme, and resulting film of gold stamped onto a silicon wafer. From Loo, *et al.*¹³ (c) Formation of a probe tip using eutectic gallium-indium (EGaIn), a non-toxic liquid metal. From Chiechi, *et al.*¹⁴

Liquid metal probes (i.e., mercury) are often used to contact damage-prone films, such as organic semiconductors. Eutectic Gallium-Indium, referred to as “EGaIn”, is a non-toxic alternative to mercury that can form a soft, non-damaging, Ohmic contact to many surfaces. Figure 4c shows the formation of a probe tip made of EGaIn.¹⁴ However, the contact area where the liquid touches the film surface is difficult to control, and also difficult to measure. Contact areas are on the order of hundreds of microns, which will still create electrical shorts through the relatively large cracks in nanocrystal films. Further, the creation of the probe tip shown here relies on the formation of a gallium oxide “skin” over the EGaIn droplet that helps to maintain the shape of the probe drop. The nanocrystals in our studies are easily oxidized, and thus must be handled and tested in an inert-atmosphere glovebox; in these conditions, the oxide skin does not form and the EGaIn probe tip is not a well-controlled size and shape.

Solution-processed techniques such as inkjet printing or screen-printing would be likely to disrupt the nanoparticle film (which is often still soluble in non-polar organic solvents due to the remaining ligand shell around the particles), and would easily short through pin-holes in the film. To make reliable, non-damaging contact to nanocrystal films, a robust method is needed that can apply an electrode that will bridge the cracks in the film, transfers reliably to a rough or uneven film, does not cause surface damage that will remove the passivating ligand shell on the nanocrystals, and does not require an interfacial adhesion layer between the electrode and the

active layer of the device. Such a method would not only be a better option for nanocrystal films, but for many other thin-film applications as well.

A New Approach: “Soft” Polydimethylsiloxane (PDMS) Stamps

Polydimethylsiloxane (PDMS) stamps have been widely used over the past decade for microcontact printing, nanotransfer printing, and other various forms of soft lithography.^{15, 16} PDMS stamps are formed by mixing a siloxane oligomer base with a curing agent, which causes the crosslinking of the polymer (Figure 5). After the PDMS is cured, some amount of unpolymerized material remains. These small oligomers are present throughout the bulk of the PDMS stamp, as well as on the surface. During the course of their studies, many groups observed that PDMS stamps contaminate the substrate with which they are brought into contact.¹⁷⁻²⁰ During contact printing, the PDMS elastomer stamps release low molecular weight oligomers that did not polymerize when the PDMS cured, which contaminates subsequent processing steps. While most groups have sought methods to reduce or eliminate the transfer of PDMS material to their substrates, some have actually used the oligomer transfer to functionalize surfaces (making them hydrophobic) and act as a pattern for subsequent printing steps.¹⁹

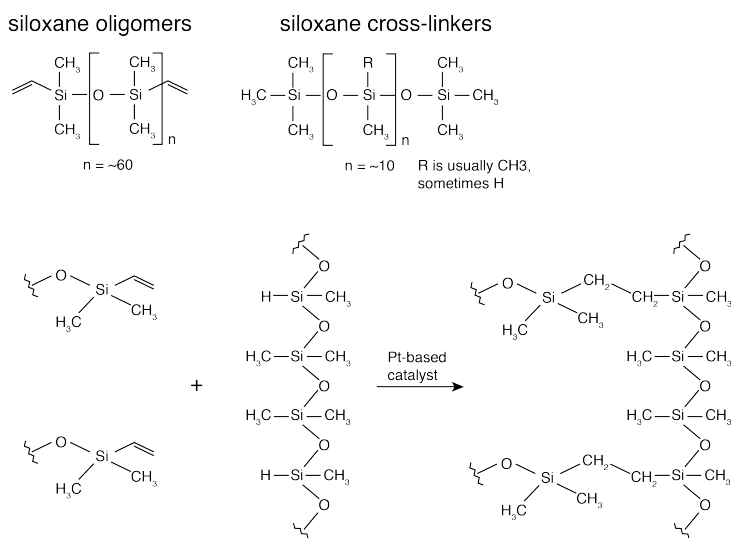


Figure 5. Polydimethylsiloxane (PDMS) is formed by mixing a siloxane oligomer base with a curing agent, resulting in the crosslinking of the polymer. Some fraction of low molecular weight oligomers do not polymerize, and as a result they are present in the stamp after curing. From Briseno, *et al.*¹⁹

The apparent difficulty others had in *preventing* the transfer of free oligomers from the PDMS stamps led us to hypothesize that the migration of the oligomers to the surface of the stamp might create a self-releasing layer between the stamp and the metal film, and aid in

transferring the metal electrodes to a device. Reducing the extent of crosslinking in the stamps would increase the concentration of oligomers in the stamp, further exaggerating the “release” effect. As an additional benefit, we expected that the reduced crosslinking would result in a softer, more flexible stamp that would provide a more conformal contact to the nanocrystal film.

Experimental Details

Nanocrystal Synthesis

We successfully obtained monodisperse, ultra-small PbSe quantum dots using a one-pot, hot injection synthesis, modified from previous methods.²¹⁻²³ Lead oxide (PbO, 99.999%), oleic acid (OA, tech. grade, 90%), and 1-octadecene (ODE, 90%), anhydrous were purchased from Aldrich and used as received. Bis(trimethylsilyl) selenide ((TMS)₂Se) was acquired from Gelest Inc. Nanocrystal synthesis was performed under argon atmosphere using standard air-free Schlenk line techniques. A solution of 223 mg PbO (1 mmol), 0.7 g oleic acid (2.5 mmol), and 10 g ODE was degassed at 100 °C in a 50 mL three-neck flask for an hour under vacuum. The solution was then heated for an additional hour to 150 °C under argon. Before injection of the selenium precursor, the solution temperature was adjusted according to the desired nanocrystal size. When the temperature stabilized, 62 μ L (TMS)₂Se (0.25 mmol) in 4 mL ODE was rapidly injected into the hot solution. Once complete, the reaction was rapidly quenched by injecting 10 mL of anhydrous hexane and submerging the flask in a room-temperature water bath. The nanocrystals used for this study were obtained with an injection temperature of 180 °C and growth time of 30 seconds, yielding particles with a diameter of $\sim$ 3nm. The nanocrystals were purified by precipitation twice in hexane/isopropanol and once in hexane/acetone and stored in hexane in an argon-filled glovebox.

Stamp Fabrication Procedure

Two types of PDMS stamps were used in this study: relief-patterned stamps and flat stamps. A silicon wafer master was prepared using standard lithographic procedures to pattern SU-8 2050, a permanent epoxy negative photoresist from MicroChem. To fabricate flat stamps, this lithography step was omitted and a clean, polished silicon wafer was used as the master. In both cases, a SAM of (tridecafluoro -1,1,2,2- tetrahydrooctyl) trichlorosilane (Gelest, Inc.) was deposited as a non-stick layer onto the wafer to allow easy removal of the cured stamp. The

PDMS stamps were made using Sylgard 184 silicone encapsulant, purchased from Dow Corning. The silicone base and curing agent were mixed in a 20:1 ratio by weight, stirred vigorously, and degassed. The mixture was poured over the silicon wafer master, degassed again, and then cured in an oven at 125°C for 20 minutes. The stamp was then cut to the desired size and placed in a thermal evaporator, where a thin (20-100 nm) layer of gold was deposited onto the surface of the stamp. The evaporation rate was optimized such that the additional curing of the PDMS as a result of heating from the evaporation step was minimized.

Solar Cell Fabrication and Testing

We adopted simple ITO/PEDOT/PbSe/Au Schottky junction device structure using PbSe nanocrystals as the only photoactive material. Patterned ITO-coated glass slides were acquired from Kintec (15 ohms/sq, ITO thickness ~150 nm). The substrates were cleaned by sonication in detergent, acetone, and isopropanol for 10 minutes in sequence, and then plasma cleaned for 5 minutes to remove any organic residue. A PEDOT film (Baytron PH, ~40 nm thick) was then spin-coated on top of the ITO surface to smooth it, and dried at 140 °C for 10 minutes. The PbSe nanocrystal film was deposited by multilayer dip-coating using a solution of quantum dots (60 mg/ml) dispersed in a 4:1 mixture of octane:hexane inside a glovebox. After each layer was deposited, the substrate was dipped briefly in a 0.001M 1,3-benzenedithiol (BDT, >98%) solution in acetonitrile to replace the oleic acid ligands with BDT. The BDT increases the coupling between particles allowing for better transport through the film, and allows deposition of additional nanocrystal layers due to the insolubility of the BDT-coated particles in the octane:hexane solution.²⁴ Gold contacts with a thickness of 100 nm were deposited by bringing a gold-coated PDMS stamp into contact with the PbSe-coated substrate in an argon-filled glovebox. While in contact, gentle pressure was applied to the back of the stamp to ensure full wetting of the stamp to the substrate, and the stamp remained in contact for approximately 3 minutes. The stamp was then slowly peeled away from the substrate, leaving the gold electrodes adhered to the PbSe. AM1.5G illumination from a Spectra Physics Oriel 300 W Solar Simulator was directed through a quartz window into an air-free glovebox, where the photovoltaic response of the devices was measured with a Keithley 236 source meter. The integrated intensity was set to 100 mW/cm² using a thermopile radiant power meter (Spectra Physics Oriel, model 70260) with fused silica window, and verified with a NREL-calibrated Hamamatsu S1787-04 diode.

Results and Discussion

Transfer-printed Metal Films

The goal of our experiment was to reduce the degree of polymerization of the PDMS stamps, thus increasing the oligomer migration to the surface of the stamp to act as the “release layer” for the gold electrodes. With this in mind, the curing conditions for the PDMS stamps were modified from the manufacturer’s recommendations to reduce the crosslinking of the PDMS. However, insufficient curing of the PDMS results in poor mechanical stability and increasing warping of the stamp during the metal evaporation step. It was determined that the best results were obtained by reducing the curing agent to half of the recommended amount (20:1 base:curing agent by weight, rather than the recommended 10:1), followed by curing for 20 minutes in a 125°C. While this recipe yields stamps that are less rigid than the standard recipe, the associated sacrifice in the minimum stamped feature size is a worthwhile trade-off to obtain a transfer method free of adhesive layers.

Two metal electrode patterns were investigated in these studies; the resulting device patterns (top view) are shown in Figure 6. The black patterns indicate the location of metal top electrodes in a finished device. The first pattern consists of a repeating pattern of 25 x 25 arrays of relief-patterned PDMS posts (100 x 100 μm each), which was the smallest device that could be reliably probed with our measurement equipment. In general, smaller device areas would reduce the need to bridge cracks in the nanocrystal film. In addition, previous studies have shown that the amount of contamination from a PDMS stamp is higher for relief-patterned stamps than for flat stamps,¹⁷ which could enhance the transfer of the metal to the substrate. However, the small size of the stamped electrodes in this case require that the device is probed directly over the ITO, introducing the possibility of shorting the device by inadvertently scratching the probe tip through the metal and QD layer to the ITO electrode beneath. Thus a second contact pattern was developed that employed large contact pads that could be probed near the edge of the substrate, where there was no ITO beneath the metal (see the cross-sectional view in Figure 6). The main drawback to the large-area pattern is that the entire pad and the connecting trace must transfer successfully from the stamp to enable measurement; a partial transfer or a crack in the trace would render that device untestable, reducing yield. This is compounded by the fact that this design only allows eight devices per substrate, compared with 625 potential devices with the pattern of small posts.

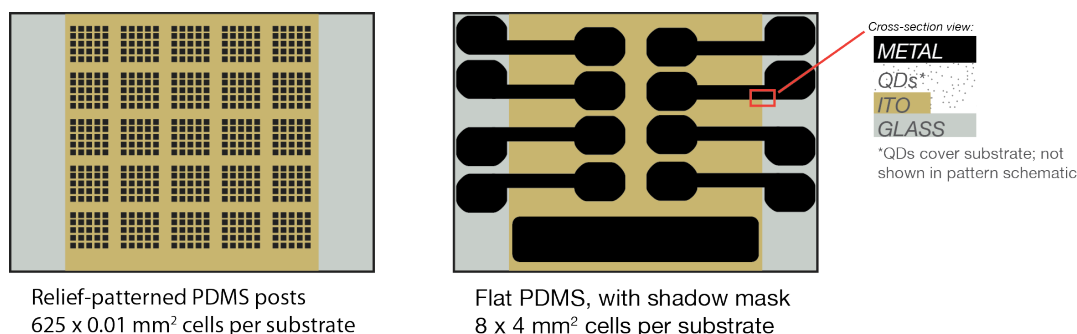


Figure 6. Device contact patterns for the transfer-printed electrodes used in this study. (Note: schematic drawings only; not to scale.)

The fabrication process for the PDMS stamps is illustrated in Figure 7. There were two main differences between the large and small contact patterns designs: 1) the small posts required a lithographically defined master to make the relief pattern in the PDMS, while a flat silicon wafer used for the larger pad design; and 2) gold was evaporated everywhere over the stamp with the posts, whereas the larger pads were patterned using the shadow mask. Figure 8a-b shows optical microscope images of the patterned SU-8 mold used as a master for the 100 μm posts. The depth profile (Figure 8c, measured by profilometry) confirms that, due to some lateral exposure of the SU-8 beneath the lithography mask, the end of the PDMS post will actually be 75 μm wide where it makes contact to the device substrate.

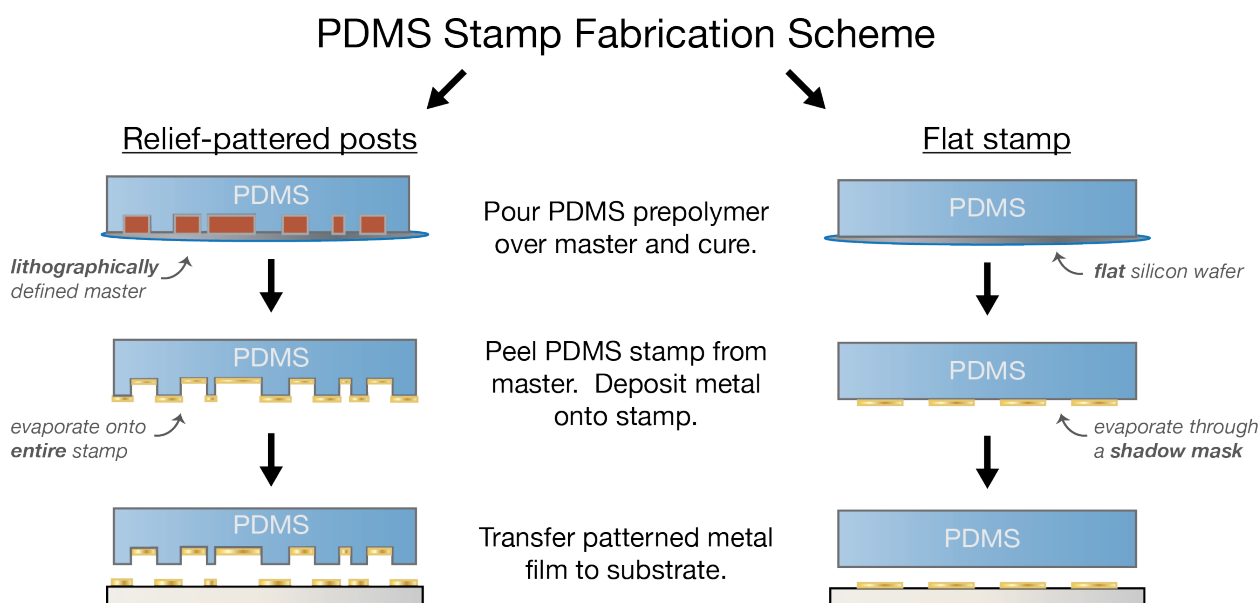


Figure 7. Fabrication steps for the PDMS stamps, illustrating the difference between the small relief-patterned post stamps (left) and the larger pads on a stamp made on a flat wafer (right).

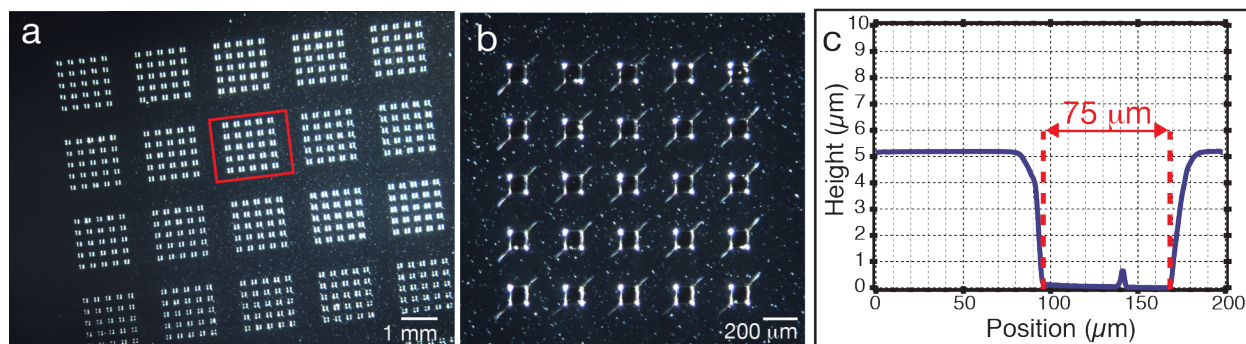


Figure 8. Optical microscope image of patterned SU-8 on a silicon wafer showing the pattern over nearly an entire substrate (a) and zoomed to show a single block (b). The depths of the patterned wells were measured by profilometry (c), which shows that the actual width of the post will be 75 μm.

Figure 9 shows optical microscope images of typical devices with transfer-printed electrodes using this soft-stamp method. Gold electrodes were successfully printed with comparable quality onto several materials including glass, poly(3,4-ethylenedioxythiophene) poly(styrenesulfonate) (PEDOT:PSS), CdS nanocrystals with octadecylphosphonic acid ligands, and PbSe nanocrystals with benzenedithiol ligands. One might expect that benzenedithiol ligands on the surface of the nanocrystals would bind strongly to a gold film, eliminating the need for the oligomer “release layer”. Interestingly, we found that even with a dithiol ligand on the nanocrystals, the release layer was necessary; using PDMS stamps cured as recommended by the manufacturer, the gold electrodes did not transfer to the substrate.

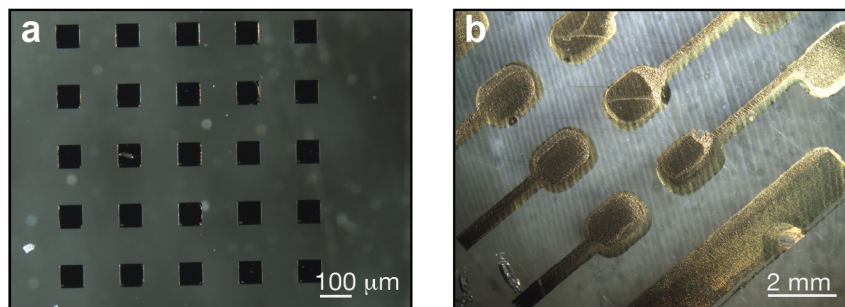


Figure 9: Optical microscope images demonstrating the transfer of gold electrodes to nanocrystal films. Relief-patterned posts are shown in *a*, while the larger pads from a flat stamp are shown in *b*.

Performance of PbSe Schottky Junction Solar Cells

Over the past four years, lead chalcogenide nanoparticles have been increasingly investigated as a candidate for low-cost, solution-processed photovoltaics.²⁵ Lead chalcogenides possess an extremely large bulk exciton Bohr radius (46 nm for PbSe and 20 nm for PbS),²⁶

which creates strong quantum confinement in colloidal nanocrystals and allows their bandgap and absorption edge to be tuned across the entire visible spectrum.^{2, 3} Fabrication of Schottky junction solar cells is straightforward with lead chalcogenide quantum dots (QDs): QDs deposited onto indium tin oxide (ITO) form an Ohmic contact, and thermally evaporating metal electrodes form the Schottky junction.^{6, 8} Devices made with this structure typically result in a solar power conversion efficiency ranging from 1-4%, with short circuit currents and open circuit voltages reaching as high as 25 mA/cm² and 600 mV, respectively.^{6, 8, 23, 27}

We used the well-studied system of PbSe quantum dot Schottky solar cells to demonstrate the usefulness of our soft-stamp transfer-printing electrode deposition method. Though aluminum is the electrode of choice for these devices, the evaporation of aluminum onto a PDMS stamp results in oxidation of the metal. The reaction between the aluminum and the elastomer stamp binds the metal to the stamp such that it cannot be successfully transfer printed. The best transfer occurred when using gold electrodes, which is known to be the best metal for transfer printing because of its low adhesion to PDMS.^{13, 28} Though the Schottky barrier height is somewhat diminished due to the larger work function, gold has still been shown to provide a rectifying contact to PbSe quantum dots.⁶

Transmission electron microscope (TEM) images of the PbSe quantum dots were taken using a FEI Tecnai G2 S-TWIN, and are shown in Figure 10. Size statistics were measured from TEM images using ImageJ software assuming spherical particles. The particles used in this study had an average diameter of 3 nm, and were encapsulated with oleic acid.

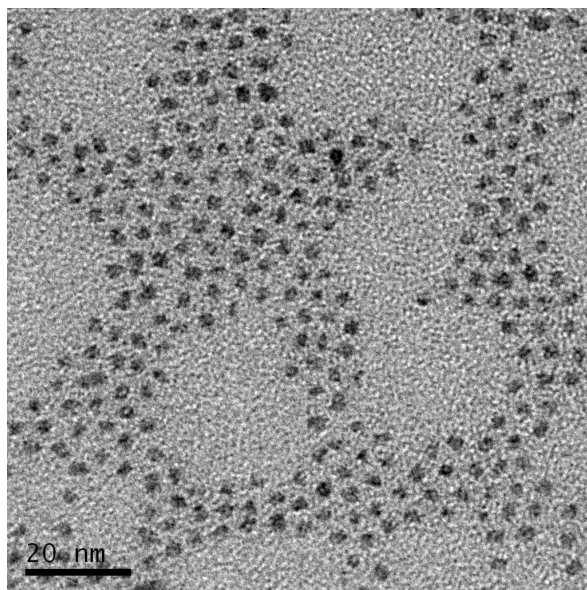


Figure 10: Transmission electron microscope (TEM) image of PbSe nanocrystals. The particles used in this study had an average diameter of 3nm.

Using our soft-stamp transfer-printing method for electrode deposition, we made solar cells with a very thin film (<30 nm) of these PbSe quantum dots. We made devices with comparable nanocrystal films, and compared the performance of our transfer-printed electrodes to evaporated gold electrodes. Our results show that for equivalent nanocrystal films, the evaporated contact makes a resistor (Figure 11a) while the stamped contact produces a device with rectification and a distinct photovoltage (Figure 11b). The failure of the evaporated electrodes on this ultra-thin film of nanocrystals is expected, based on the results discussed previously from Trudeau *et al.*¹¹ Also as we expect, the performance of the un-optimized stamped devices is significantly worse than many of the published PbSe solar cell results – the small Schottky barrier of the gold on the PbSe and the loss in absorption in the ultra-thin photoactive layer reduces the overall power conversion efficiency from a typical value of 3% to less than 0.1%. Nonetheless, this does illustrate that the soft-stamping method can successfully deposit electrodes onto thin-film devices without diffusing metal into the nanocrystals or shorting through pin-holes in the film.

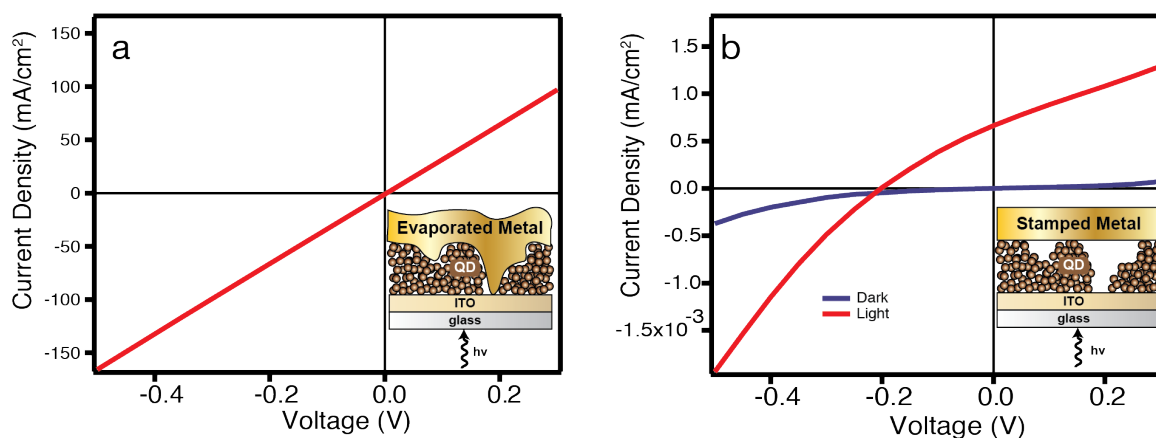


Figure 11: Performance of PbSe Schottky solar cells, comparing evaporated gold electrodes (a) with transfer-printed gold electrodes (b).

Conclusions

Presented here is an alternative method for electrically contacting semiconductor nanocrystal thin films using elastomeric stamps, where transfer of the metal to the substrate does not require an interfacial adhesion layer. The elastomeric stamp contact deposition method not only allows reproducible contacts to materials prone to pin-holes, but also enables thinner layers of active material, which could benefit thin film solar cells that suffer from short carrier diffusion lengths.

While nanocrystals hold great promise, the large surface area of individual nanocrystals, a high concentration of interface states, and the insulating organic ligands remaining in the film hinder their usefulness in electrical devices. Future studies to investigate passivating the nanocrystal surfaces or to develop low-temperature sintering methods will enhance their performance in electrical devices and provide new pathways to low-cost, solution-processed electronics.

Acknowledgments

I gratefully acknowledge my group members in the Alivisatos lab – particularly Jessy (Baker) Rivest, Jesse Engel, Brandon Beberwyck, Trevor Ewers, Wanli Ma, Ming Lee Tang, and Prashant Jain – for helpful discussions and collaborations. I thank Paul Alivisatos for his

guidance and encouragement. This work was supported by a Graduate Research Fellowship from the National Science Foundation, and by the DOE 'Light-Material Interactions in Energy Conversion' Energy Frontier Research Center under grant DE-SC0001293.

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