Low-Cost Selective Deposition of Wax Onto Textured Solar Cells

by

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Submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of Bachelor of Science in Mechanical Engineering at the MASSACHUSETTS INSTITUTE OF TECHNOLOGY June 2008

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Abstract

The active regions of a solar cell must be inoculated with wax, while leaving the metal fingers and bus bars bare, in preparation for the electroplating step of a new solar panel manufacturing process. Different methods to achieve the inoculation of the cell are discussed, along with their advantages and disadvantages. A proposed solution is presented, along with results from test runs.

The methods use a new feature of solar cells—microscopic, light-trapping textures—to passively wick the liquid wax to the extents of the regions through capillarity. Using this self-aligning feature of the cell texture, a low-cost delivery device was designed to bring liquid wax beads to within close proximities of the surface, without requiring high-precision equipment. The prototype uses an array of pins of diameter 1 mm, each of which beads a repeatable amount of wax on its head (~ 0.1 mg), to transport the liquid wax from reservoir to cell texture. No metal-to-wafer contact is done in the process. The design has been used as a basis to create a machine at the Photovoltaics Laboratory (PV Lab). Successful inoculation of monocrystalline solar cells has been achieved using the proposed method.

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Title: Fred Fort Flowers and Daniel Fort Flowers Professor of Mechanical Engineering
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Chapter 1

Project summary and history

The purpose of this project is to create a low cost, scalable, and reliable method for applying a wax mask to a solar cell as a step in the manufacturing of the cells and, ultimately, solar panels. Tiny channels in the texture act as capillaries directing the liquid wax to the edges of the site being inoculated. The method utilizes this unique cell texture to produce repeatable results by utilizing its self-aligning nature. Letting the texture do the precision work means that the efforts can be directed towards delivering the right amount of liquid wax to the site. In addition, it reduces the need for high-precision equipment, thereby reducing costs both in production and maintenance.

In investigating the best technique for wax delivery, several strategies were deployed. Ease of construction, manufacturing costs, and scalability (both to greater and smaller scales) were factors in determining the best strategy.

Because these solar cells are manufactured differently from present technologies, there are no previous working methods for this purpose.

1.1 Cell texture and capillarity

The texture on a solar cell consists of fine troughs, or channels, that conduct liquids using capillarity. Due to this property, it is only necessary to apply sufficient liquid wax at strategic points near the center of the region to be inoculated (active region or site) to effectively inoculate the entire site.
Cell texture plays an important role in the procedure, since different textures channel the wax differently. Throughout most of the testing phase, it was assumed that changing cell texture was not an option. This assumption was based on a need to decouple the inoculation step from other design parameters extraneous to this project.

### 1.2 Solar wafer characteristics

The pertinent features of the test solar cell, including texture description and dimensions, are shown in Figure 1-1.

Production solar cells are larger than those used for testing in this work, so the method must be scalable. In addition, future designs could include thinner strips, so the method should also scale in the strip width direction (see Figure 1-1).

### 1.3 Functional Requirements

Successful wax inoculation of the solar cells requires:

- Each individual strip completely covered with wax,
- Only active sites covered with wax (no “spill overs” into fingers or bus bars),
- Adequate for a strip width of 2 mm, and scalable to 1 mm strip width,
- No damage to cell or texture during application.

In particular, the chosen method must also adhere to the following guidelines:
• Liquid application of wax (~ 60° C),
• No “hard” surface contact with cell,
• Repeatable method and results,
• Accurate dispensing, and
• Relative low-cost and simplicity.

1.3.1 Amount of wax per strip

For a strip 2 mm wide and 10 mm long, the amount of wax required for successful inoculation is ~ 1 mg. This was determined empirically by mass averaging. Because of scalability, the method of delivery must be divisible into small units that can be chained together to accommodate any length strip. This implies that each unit cell of wax delivery must be able to retain an amount on the order of tenths of milligrams of wax.

1.4 Nomenclature

The following conventions are used in this document:

Solar Cell Silicon wafer that has been etched in order to create active regions, metal fingers, and bus bars, and which have also been nitride coated.

Texture Light-trapping grooves in active regions of the solar cell (Figure 1-1).

Active region, strip Individual section of solar cell to be inoculated (Figure 1-1).

Inoculation Complete covering of active regions of cell.

Spill over Presence of wax in non-active regions of the cell, such as the fingers or the bus bars.
Chapter 2

Different Methods of Inoculation

Various methods of wax inoculation were considered. The most difficult functional requirement to meet was that of hot wax application, since this mandated that the delivery apparatus remain warm during the process. The requirement of no direct contact with the solar cell could be met by ascertaining that the wet wax, and not the delivery apparatus, made contact with the cell.

In general, the different delivery methods considered used capillarity and surface tension in the wax to not only wick to the hot surface of the solar cell, but to adhere—and bead to—the delivery mechanism.

The different delivery strategies tested were:

- Closed geometries (Section 2.1),
- Pin heads (Section 2.2.1),
- Drill flutes (Section 2.2.2),
- Combs (Section 2.2.3).

2.1 Closed Geometries

Closed geometries refers to all variations of pipes, hypodermic needles, and other such elements with internal walls used in the delivery of liquids.
One attractive feature of this method is the possibility of great precision which has been previously readily obtained (e.g. drug delivery in syringes).

At the scale of delivery necessary, however, internal geometries pose challenges for the maintainability of the mechanism. For instance, a dust particle clogging any one of the multiple tubes would render the entire device unusable. In addition, the small amounts of wax that each tube would deliver required the opening to be of a diameter where capillarity within the tube would work against the capillarity of the cell textures.

The strong capillarity within the tubes requires a significant pressure to force the liquid wax out. In addition, to avoid direct contact between tube and silicon wafer during delivery, a bead must be formed on the tip, and this bead must be reliably of the same size for every tube.

2.2 External Geometries

2.2.1 Pin Heads

The complexity of the internal geometries can be bypassed by using the wax surface tension to create a bead on an appropriately dimensioned head (like that of a sewing pin). Such a configuration is shown in Figure 2-1.

The amount of wax that can bead to the head of the pin is related to the surface tension
of the material through a force balance,

\[ m \approx \frac{\pi d \gamma}{g}, \]  

(2.1)

where \( \gamma \) is the surface tension of the wax, \( d \) is the pin head diameter, and \( m \) is the mass of wax\(^1\). Using (2.1) and experimental data, the correct head diameter was determined to range from 0.75-1.10 mm, or equivalently, a drill ranging in size from #70 to #60 (1.01 mm).

**Test Results**

Typical results of the pin head deliver method using a #70 drill blank are shown in Figure 2-2. The superimposed circle shows the relative size of the drill blank. Note that the resultant inoculated section is no wider than the diameter of the pin. This is due to the lack of communication across channels in the texture, so that as soon as the wax bead makes contact with the hot surface, the liquid wax is sucked out to the edges of the strip.

Increasing the size of the pin head to deliver more wax resulted in persistent spill over into the metal fingers. A fundamental reason for this tendency is the immediate capillarity pull of the center of the bead of the wax, as opposed to its perimeter, so that a bigger pin

\(^1\) (2.1) is only an approximation because contact angle also factors in the expression.
head results in more wax being sent across the width of the strip, but not across its length.

This is the paradox of the pin head as a delivery method: how to deliver more wax in order to cover a bigger section with each dip of the head, while maintaining the diameter of the pin head so as to prevent spill over. Because the physics for the beading process are fairly well described by (2.1), the only way to increase the mass of the wax is to increase pin head diameter $d$. But increasing the diameter beyond 1 mm leads consistently to spill over.

### 2.2.2 Drill flutes

It is possible to collect wax by having it run up the flutes of a drill through capillarity, as in Figure 2-3. This would allow each drill to hold a significantly greater amount of wax without increasing head size. The capillarity of the wafer texture would still be greater than that of the drill flutes, due to its finer structure.

To study this effect, several styles of drills with different flute lengths were brought to temperature and dipped into a bath of wax. The amount of wax that can crawl up the flutes is controlled by surface tension and gravity. If the drill is brought to the surface of the liquid wax, the wax would naturally crawl up the flutes a height $h$.

If the drill is then dipped a distance $h_d$ into the wax, then upon removal, the total height of the wax column in the drill would be $h + h_d$, which is more than the equilibrium amount. This would cause the excess wax to run down the drill thereby forming a bead on the head.
This bead could then be used to initiate the wax extraction process upon touching the hot textured surface (Figure 2-3).

There were several problems when this method was put into practice. First, the suction up the flutes was less than expected. Even more important, there was great resistance against running down the flutes, so that no beading occurred. Finally, because of the reluctance of the wax to run down the flutes, the wafer texture was unable to extract a significant amount of wax from the drill.

Throughout these tests the drills were maintained in a 100°C environment, well above the melting point of the wax.

2.2.3 Nit comb

Another strategy for external conveyance was the use of closely spaced pins—like the teeth of a nit comb—which would trap the wax in the space between them by capillarity. The difference between this method and the drill flutes is a vertical wax column instead of a helical one, where resistance to run down (and beading) is greater.

The trial nit comb had a geometry as shown in Figure 2-4.

The space between teeth was 0.15 mm. At this gap size, the comb collected too much wax for deposition: the natural height that the wax column attains with no constraints \( h \), was greater than the length of the nit comb teeth.
Figure 2-5: Capillarity in the gap between teeth of nit combs with spacing as shown. The meniscus shown was a drawback to the concept because it produced an “inverted bead.”

2.2.4 Wider spacing techniques

To remedy the problem of too much wax collection in the nit comb, other prototypes with wider spacing were constructed. Using readily available materials including metal prongs from electronic devices, three combs with different spacings were assembled.

The three different combs were dipped hot into liquid wax. Consistent wax in the nit comb gaps was only achieved for the smallest (0.10 mm) gap size. Results were sporadic in the case of the medium width (0.20 mm) and scarce in the widest (0.30 mm). Whenever present, the column of wax did not produce any bead in any of the combs, despite comb lengths greater than \( h \) and the expected bead effect of Figure 2-3. Instead, the wax formed the “inverted bead”, or meniscus in Figure 2-5.

This experiment revealed the tight tolerances required for capillarity in the gap to work at all. Variations in the order of a tenth of a millimeter are enough to render the process unrepeatable. Moreover, the inability to form a bead was a serious detriment to the no contact functional requirement.
Chapter 3

Working prototype

Of the methods described in Chapter 2, none had the repeatability, or showed as much promise, as the pin method (Section 2.2.1).

As discussed earlier in Section 2.2.1, the main drawback to this method was a resulting inoculation width that was no larger than the pin head itself (Figure 2-2). It is not possible to inoculate one strip in one shot, because the pins need to be spaced apart sufficiently to avoid capillarity as in the nit comb concept (Section 2.2.3). A work around to this spacing requirement is to inoculate each strip in two passes each with half as many pins.

Another solution is to alter the texture of the cell such that the wax is not restricted to one channel, but able to flow to adjacent ones by means of cross-communicating channels.

3.1 Texture with communicating channels

By adding communication channels to the cell texture as shown in Figure 3-1, two problems were addressed at once.

Figure 3-1: Communicating channels in new wafer texture
Figure 3-2: Design for graphite substrate. Spacing controlled in one direction by size of inoculated region, and in another by spacing of the strips on the cell.

First, it would be possible to inoculate a section of wafer that was greater than the diameter of the pin, eliminating the need to distribute the pins over two rows. Also, the new communicating channels would provide greater flexibility in the amount of wax that each individual pin carries, since the wax would not be confined to a region but able to distribute along the entire strip. This translates to fewer spill overs.¹

Simple tests with the same pins as in Section 2.2.1 and the new texture corroborated these hypotheses. The result was a more rounded inoculation pattern instead of the rectangular patterns of Figure 2-2. In addition, the section of strip inoculated was now approximately twice the diameter of the pin, making one row of pins sufficient to cover one strip of wafer.

### 3.2 Apparatus design

Based on the percent of inoculated strip and the parameters of the solar cell (described in Section 1.2) a prototype apparatus was designed and built.

The design consisted of a 2D array of pins (drill blanks) press fit into a graphite substrate that was kept at temperature with power resistors. Graphite was chosen for machinability and high thermal conductivity. The design is shown in Figure 3-2.

The drill blanks, or pins, were pressed fit to ascertain good thermal contact with the graphite substrate. They were also cut down to length in the later prototypes to minimize

¹This effect was greater improved by providing a "buffer" channel at the edges of the active region. See Section 4.1 for details.
heat losses due to cooling fin effects. It is important that the tip of the pins are kept hot (above 60° C) so that the wax remains liquid at all times. If the wax freezes, cross-links can occur as the wax fills the gaps in between the pins (similar to a 2D nit comb) and they cease to work as individual units.

A prototype meant for selective inoculation of a single strip is shown in Figure 3-3. Note that the pins in the figure have not been cut to length. The power resistors shown are 5 W each. Also visible in the figure is the hot plate and part of a micro stage, used for controlled vertical positioning of the pins. The amber plastic that attaches the graphite substrate to the micro stage is a piece of Ultem® plastic. It was chosen for its ability to withstand high temperatures (glass temperature: 215° C) and low thermal conductivity (0.122 W/m – K).

### 3.3 Prototype run: single strip

The apparatus shown in Figure 3-3 was used to carry out a test run. The total power input was 8 Watts\(^2\). The solar cell was placed on the hot plate set to 100° C. The pins were dipped in liquid wax as shown in Figure 3-4. The pins were then aligned by eye with the strip of

\(^2\)This value can be greatly reduced with design refinements
the wafer and lowered to the level of the cell texture with the micro stage (Figure 3-5).

The resulting inoculated strip is shown in Figure 3-6.

3.3.1 Run results: meniscus interaction

There is a noticeable spill over on the bottom right edge of the strip. Upon closer inspection, this spill over was caused by defects in the texture where the wall was not well defined, such that the texture and the finger to which the wax spilled were effectively in communication.

Visible in Figure 3-5 is that the pins did not all bead the same amount of wax. While it is true that for a texture with communicating channels there is tolerance to the amount of wax each pin needs to carry, the deviation from pin to pin posed some concern.

Tests involving dipping a single pin in the molten wax produced no noticeable deviations in the bead produced. This implied that the discrepancy shown in Figure 3-5 and in subsequent tests was too large to be attributed to normal deviations in pin head geometry and unevenness of pin heights. Testing with two adjacent pins revealed that the menisci of the pins as they were pulled out of the liquid wax bath were interacting and influencing one another (Figure 3-7).

Because of this interaction, in a row of pins, when one of the menisci “snapped” it
Figure 3-5: Lowering the pins to solar cell surface. Pins were aligned by eye and lowered using micro stage.

Figure 3-6: Inoculated strip using pin array method
caused the adjacent ones to snap too, at times prematurely. The result is less wax beading on some of the pins. Other forms of interaction include fluid disturbances caused by the snapping action. When a meniscus snaps, it sends tiny waves through the liquid wax that propagate and disturb the fragile, adjacent menisci.

### 3.3.2 Proposed solution for meniscus interaction

The problem of interacting menisci can be readily solved by isolating the dipping process so that each pin has its own tiny, non-communal well. Extrapolating this idea, one can imagine a screen, or mesh that is overlayed on the liquid wax reservoir to segregate the individual pins.

This, and other refinements, are subjects of future research. The proof of concept is demonstrated in Figure 3-6, and in follow-up work at the MIT Photovoltaics Laboratory.
4.1 Subsequent research in pin delivery system

Subsequent work has been done at the Photovoltaics Laboratory in extrapolating the pin delivery concept to inoculate an entire cell at once, and eventually, full scale production, including the addition of a buffer channel at the edges of the strips.

4.1.1 Adding buffer channel to texture

Spill overs can be minimized by adding communicating channels at the edges of the strips. These channels, similar in geometry to the communication channels (Section 3.1), even out discrepancies in the quantity of wax delivered to the edges of the strip.

![Diagram](image)

Figure 4-1: Additional buffer communication channel at edges of strip prevents spill overs.
4.1.2 Full cell apparatus

Based on the design parameters discussed in Section 3.2, a full cell machine was built. Figure 4-2 shows the results of inoculating a solar cell made of mono-crystalline silicon using such machine.

4.2 Concluding remarks: a work in progress

Exploiting the inherent capillarity of the fine light trapping texture of a new type of solar cell, a mechanism for wax inoculation of solar wafers was created which focused on the repeatable and precise delivery of the liquid wax. The concept consists of a two-dimensional array of pins each of which bead a controlled amount of wax using surface tension. The nature of the process makes the delivery mechanism scalable without bounds in one direction (length of the strip) and within an order of magnitude in the other (width of the strip).
While various concepts were tested, none were as simple or as promising as the pin array method. The mechanism was used to successfully inoculate a strip of solar cell. Subsequent work by other researchers extrapolated this design to inoculate an entire cell. The success of the mechanism required alterations to the cell texture.

Inoculating the solar cells with wax allows for a cheaper manufacturing process using electroplating techniques in lieu of silver printing. Driving costs down, while increasing efficiency, is a major step towards the feasibility of photovoltaics as an energy source. Simple manufacturing methods, like the pin-delivery mechanism, pave the way to making photovoltaics, and solar panels, a competitive technology in supplying the growing world energy demands.