DESIGN OF CdTe THIN FILM SOLAR CELL AND BASIS OF ITS EMERGENCE AS SIGNIFICANT FACTOR IN GRID ELECTRICITY CAPACITY

In order for solar power to constitute 10% of US energy use, the growth of large scale, grid-connected photovoltaic systems must be ensured and promoted. Though the number of residential grid-connected installations is eight times that of commercial and utility installations, in terms of power capacity, nonresidential grid-connected installations account for over 50% of capacity added per year. In fact, in 2008 nonresidential installations accounted for 73% of new grid-connected PV systems (Sherwood 2009):

Graph of installed grid-connected PV by sector, 1999-2008, removed due to copyright restrictions.
Please see Fig. 2 in Sherwood, Larry. "U.S. Solar Market Trends 2008." Interstate Renewable Energy Council, July 2009.

Figure IV. 1: Capacity installed (MW) per year by sector

It becomes clear that the promotion of large scale, grid-connected PV systems will have the overall effect of significantly promoting the growth of the solar industry within the US. What, then, is limiting the growth of these solar farms? It is not land area because these solar power stations can be built in abandoned fields outside of crowded cities. Rather, the key constraint here is the installation cost. Because of this constraint, cadmium telluride (CdTe) thin film solar cells, which have the lowest manufacturing cost of all the commercial solar cells, were chosen as the platform for expanding solar power stations. To continue in reducing costs, and thereby increase solar power capacity, it is necessary to improve solar cell efficiency and minimize manufacturing cost through superior cell design and streamlined module production.

In choosing CdTe as the semiconductor material for our solar cells, issues of toxicity and scarcity are quickly raised. Because cadmium is highly toxic, if there exists a possibility of human exposure to cadmium from these solar cells, CdTe should be discarded in favor of another, non-toxic semiconductor material. In a report by Fthenakis (2003), however, it is stated that only 10% of cadmium is wasted in the manufacturing production, waste which is recycled or safely

disposed of. Additionally, the use of HEPA filters reduce airborne emissions to 3g of cadmium per ton of cadmium used. Exposure to cadmium during PV use is also highly unlikely. Steinberger (1997) concluded that exposure is not likely to occur during accidental breakages. For cadmium disposal at the module's end of life, all CdTe manufacturers in the US have a recycling program in place. As for scarcity concerns, the tellurium in CdTe cells is not an abundant resource. Tellurium is also used by other industries, but a report conducted by NREL (1999) declares that tellurium use by non-PV industries has actually decreased over time. In this same report, NREL calculated that 859 to 1716 metric tons of Te are available annually as a byproduct of copper mining, in addition to an estimated 24,000 metric tons of Te tied in with copper in US reserves. For CdTe cells with 10% efficiency, to create 1GW of cells requires 93 metric tons of Te. For our goal of 225GW, 20,925 tons of Te are necessary and, assuming an annual supply of 1000 tons, our goal is attainable within 20 years. The reserves cover the needed volume of Te, but if we hope to continue to expand solar energy use using CdTe cells, there needs to be a more reliable source of Te. Tellurium is also a byproduct of other metals mining such as lead, gold, and platinum. Because the demand for Te has been below the possible supply, the investigation of Te supplies from sources other than copper has been lacking. To ensure a steady supply of Te, we need to increase the mining of copper and other metals that may additionally yield tellurium. Another factor to consider with scarcity is price. If the price of tellurium is too high because of its scarcity, it would not be economically feasible to use CdTe for our solar cells. The report by NREL also states that tellurium consists of only 3% of manufacturing costs; for tellurium to reach a point where it is financial unsustainable would be if it consisted of 24% of costs, or if tellurium cost was eight times the current cost. To prevent the price from reaching that point, the government must subsidize this industry, which is not an unreasonable expectation since all major industries (oil, agriculture, etc.) require subsidization to thrive.

Figure IV. 2: Schematic of our CdTe solar cell

Having established CdTe as sustainable, there are a plethora of reasons for why CdTe is an excellent choice for use in our solar cells. CdTe has a direct band gap of 1.47 eV, meaning CdTe is more efficient at converting photon energy into electrical energy (as opposed to silicon which has an indirect band gap of 1.1 eV). Its high absorption coefficient translates into a small thickness of semiconductor material required, making it suited for the production of thin film solar cells, which have the cost advantage over cells created from thick wafers. Considering all of these properties, a thin film CdTe solar cell has a theoretical efficiency of at least 20%. This cell would be able to extract 0.02W per square meter from solar energy, and to generate 225 GW would only require 4344 square miles of solar cells.

Even though the theoretical efficiency of a CdTe thin film is approximately 20%, a commercial CdTe cell has only an efficiency of 11%. To rectify this difference, the solar cells created should be designed so as to mirror the ideal solar cell generated in our PC1D simulator. A schematic of our proposed cell is detailed to the left (not to scale):

When using the PC1D simulation, there was no CdTe materials file to choose from, and so we took the GaAs file and changed the band gap, index of refraction, and carrier lifetime to 1.47 eV, 2.67, and 0.01μm respectively to simulate CdTe. Another problem encountered was with the p-n junction. Unlike silicon, the p-n junction of CdTe cells is created with the joining of two different chemical compounds: CdTe (p-type) and CdS (n-type). The simulator does not seem to be able to accommodate this feature, so we doped the cell normally and factored in the separate material under where we entered the anti-reflective coating (n = 2.51). A thickness of 70 nm was chosen because any smaller or any larger decreases both the short circuit current and open circuit voltage, decreasing efficiency and fill factor. We also entered a 10,000 nm layer of glass (n = 1.52) to be considered in the antireflective coating because all CdTe cells are created on a comparatively large glass superstrate.

In terms of other parameters, using a standard 100 cm^2 device area, the thickness of the semiconductor CdTe was chosen to be 5 micrometers. Decreasing down to 4 micrometers decreases short circuit current by 0.02 amps; increasing to 6 micrometers increases short circuit current but also decreases open circuit voltage. There is an ideal thickness for these cells because if it is too thin, there is not a sufficient distance for the wavelengths of light to be absorbed, and less free carriers are generated, and short circuit current decreases; if it is too thick, short circuit current does increase, but open circuit voltage decreases by a greater magnitude, decreasing efficiency. A thickness of 5 microns is greater than the typical 3 microns for commercial cells; a possible reason could be that if financial concerns were kept in mind (which they always are), a thickness of 3 microns would be entail lesser costs, because of lesser quantities of CdTe used, with minimal effects (efficiency only decrease 0.14%). The p-type doping chosen was 10^{16} cm^{-3}; deviating from this value decreases short circuit current, and efficiency, because below this value, more holes can continue to be added to increase current, and above this value, free carrier absorption occurs. The n-type doping was given a depth factor of 0.07 micrometers (the thickness of our CdS layer) and peak doping of 10^{19} cm^{-3} for the same reasons as above. The maximum added efficiency when incorporating surface texturing was 0.1%, which occurred for a depth of 0.1 micrometers. Because the economic costs and manufacturing adjustments associated with incorporating such small texturing outbalance the possible benefits, we decided not to texture the surface of our solar cell. As for an anti-reflective coating, it would be wedged between the glass and CdS layer and would ideally have an index of refraction of $(2.51*1.52)^{1/2}$ = 1.95. We also need to consider the fact that a front metal contact needs to be placed between these materials, and it happens that SnO_2, the typical choice, has an n = 2.00, close to our desired value. Ideally, the thickness of the AR coating should be an odd multiple of ($\lambda/4n$ = 70 nm), where λ equals 555 nm (the wavelength from the sun with maximum intensity). A metal contact layer of 70 nm, however, would not be sufficiently thick enough to be an effective front metal

contact, so a thickness of 500 nm (approximately 7*70 nm) was chosen. Taken altogether, these parameters create a solar cell with a characteristic efficiency of 22.34%.

DEVICE
Device area: 100 cm^2
No surface texturing
No surface charge
Front surface optically coated
No Exterior Rear Reflectance
No internal optical reflectance
Emitter contact enabled
Base contact enabled
No internal shunt elements

REGION 1
Thickness: 5 μm
Material modified from gaas.mat
  Carrier mobilities from internal model
  Dielectric constant: 10.9
  Band gap: 1.47 eV
  Intrinsic conc. at 300 K: 2.59×10^6 cm^{-3}
  Refractive index: 2.67
  Absorption coeff. from internal model
  No free carrier absorption
P-type background doping: 1×10^{16} cm^{-3}
  1st front diff.: N-type, 1×10^{19} cm^{-3} peak
  No 2nd front diffusion
  No rear diffusion
Bulk recombination: $\tau_n = \tau_p = 0.01$ μs

RESULTS
Short-circuit Ib: -2.933 amps
Max base power out: 2.234 watts

Figure IV. 3: Input parameters into and results from PC1D simulation

Not only can a high efficiency create a cost effective solar cell, but also, a streamlined manufacturing process can decrease manufacturing costs to be competitive with other energy fuel types. The key advantage of CdTe cells is the ability to quickly manufacture high quantities of solar modules. It takes less than two hours to produce a solar module and costs less than $1 per watt. CdTe cells are created with a process called vapor transport deposition. Once a glass superstrate has been created, and a tin dioxide layer has been coated on, this glass and metal are placed on a conveyor belt. This conveyor belt sends the glass and metal through four chambers:

Figure IV. 4: Sketch of vapor deposition conveyor belt (Nolan and Meyers)
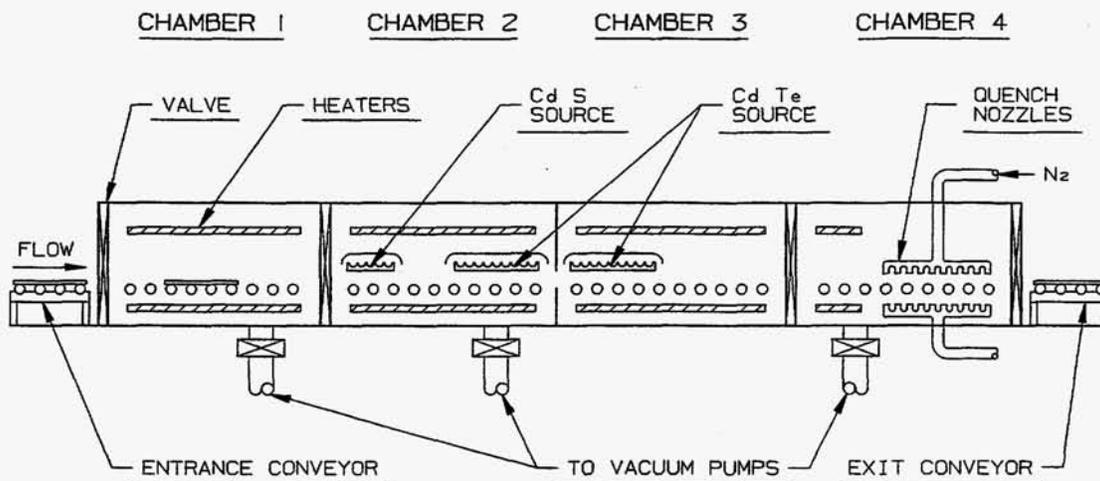
The glass is conveyed into the first chamber. A vacuum is created, and heaters raise the temperature of the glass to 600 degrees Celsius. The glass is then moved to the second chamber where powdered CdS lies above it. Once sealed off, this chamber is raised to a temperature of 700 degrees Celsius, at which point the CdS vaporizes and is deposited onto the glass superstrate. Once the CdS has been deposited (a process only taking 10 seconds), it continues, and CdTe is deposited over the CdS layer in the same manner as the CdS layer deposition (a process only taking 40 seconds). The module now moves to chamber four, where it is quickly cooled off with nitrogen gas, which also has the added benefit of tempering and strengthening the glass. Once the pressure from the nitrogen gas has dropped down to atmospheric pressure, the exit value is opened, and fans outside are sufficient for the cooling of the module. After the module has cooled to room temperature, the back contact is deposited by sputtering, and the glass backing is attached with a laminate. The bulk of this process can be fully automated, reducing the necessary labor and the overall manufacturing costs. It also outputs a solar module within a short timespan, and this high throughput reduces the overall manufacturing costs. That the process of cadmium deposition occurs within a vacuum also minimizes risk of cadmium emissions into the environment. The manufacturing of CdTe solar modules is characterized by a high throughput and low labor costs, both totaling to yield a low cost solar cell which is ideal for integration into large solar power stations.

Only if the growth of the CdTe cell industry has the possibility of meeting future energy needs should CdTe be implemented as the standardized cell for large, grid-connected PV systems. For simplicity, we are assuming that all solar cells made in the US are sold to only US consumers. Considering that FirstSolar (the leading CdTe producer) has five other high yield plants in Germany and Malaysia, this assumption entails a conservative estimate. There are two CdTe factories within the US: FirstSolar (223MW) in Perrysburg, Ohio and Abound Solar (currently operating at 65MW, despite that 200MW are possible) in Longmont, Colorado. A model based on this data would be based on an initial production capacity of 288MW per year with a growth rate of 20%. FirstSolar's mean growth rate is 60%, but their standard deviation is 50%, and so a

growth rate of 20% was assumed as a reasonable estimate (Fast Facts 2010). A model for factory growth would, therefore, be $f(t) = 0.288e^{0.2t}$ with units of GW. Integrating this equation would give us a model for cumulative installed PV systems, which yields an equation of $g(t) = 1.44e^{0.2t}$. Our goal of 225GW, then, is achievable within 28 years. With any dramatic change in infrastructure, as a 10% derivation of power from solar would surely be, issues like backwards compatibility (solar panels produce DC current whereas the grid puts out AC current), sufficient financial backing (entry into the solar industry requires high initial investments), and decisive government action (mandates and subsidies promoting solar energy and discouraging fossil fuel-based energies) must be addressed as soon as possible. Without a concerted effort by the government, the industries, and the consumers, solar energy may never gain a foothold in the US but working towards a common goal of energy independence and green living, both of which are possible with the expansion of solar power stations, for solar energy to comprise 10% of our energy consumption will be achievable within 50 years.

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