A Market Analysis for High Efficiency Multi-Junction Solar Cells Grown on SiGe

By

Zachary Steele Judkins

B.A., Physics (2006)

University of California at Berkeley

Submitted to the Department of Materials Science and Engineering in Partial Fulfillment of the Requirements for the Degree of Masters of Engineering in Materials Science and Engineering

at the

Massachusetts Institute of Technology

September 2007

Signature of Author...
Department of Materials Science and Engineering

Certified by...
Eugene Fitzgerald
Merton C. Flemings-SMA Professor of Materials Science and Engineering
Thesis Supervisor

Accepted by...
Professor Samuel Allen

A Market Analysis for High Efficiency Multi-Junction Solar Cells Grown on SiGe

By

Zachary Steele Judkins

Submitted to the Department of Materials Science and Engineering in Partial Fulfillment of the Requirements for the Degree of Masters of Engineering in Materials Science and Engineering

ABSTRACT

Applications, markets and a cost model are presented for III-V multi-junction solar cells built on compositionally graded SiGe buffer layers currently being developed by professors Steven Ringell of Ohio State University and Eugene Fitzgerald of MIT. Potential markets are similar to those currently occupied by high efficiency multi-junction space solar cells grown on a Germanium substrate. Initial cost analysis shows that at production volumes similar to those of the state of the art, cost could be reduced by a factor of four. Significant market share may be gained in both the space and terrestrial PV markets due to improved performance associated with superior materials properties advantages as well as production cost reductions.

Acknowledgments

I would like to thank the Department of Materials Science and Engineering at MIT for it's financial support which made my participation in the M.Eng. program possible. Stephanie Bright and Angelita Mireles for their diligence, Professor Carl Thompson for his guidance in selecting courses that best fit my interests, and guiding me to Professor Eugene Fitzgerald, my research advisor.

Professor Fitzgerald deserves thanks for his enduring support and guidance. His technology provided me with a project more fitting than I could have every hoped for when applying to this program. The experience and knowledge I have gained through this project will certainly prove invaluable, and for that I thank him as well.

I would also like to thank my family. My mother, father and the Holland family have provided endless encouragement in all of my educational endeavors. They have been the robust substrate onto which I have been precisely grown.

Chapter 1—Introduction

Motivation

Technology being developed at MIT shows great potential for progressing the technology of and markets for high-efficiency multi-junction (HEMJ) solar cells. Currently, HEMJ cells are grown on a Ge or III-V compound substrate. This is less than ideal for a number of manufacturing, cost and performance considerations; a SiGe, or virtual Ge, substrate created by compositionally grading Si from 100% Si to 90% Ge over the length scale of tens of microns may be superior. Development has been underway for over a decade, laboratory and field-testing has shown that performance will soon be at least on par with the state of the art.

HEMJ solar cells are the most advanced photovoltaic devices to be commercially produced since the inception of the photovoltaic industry in the 1950's. To date, HEMJ cells have been cost prohibitive to all but the most performance demanding markets, namely, on board power for orbiting and deep space satellite missions. The first multi-junction solar cell was developed for space power in the late eighties, and in the past decade HEMJ cells with efficiencies nearing 30% have become the industry standard, for all intents and purposes replacing single junction Si technology. Although there are smaller niche markets that may take advantage of HEMJ devices, outside of satellite power, they have for the most part been merely a laboratory curiosity.

This trend may be changing, however, as technological advances are made and the economics of the energy sector evolve. Fossil fuel prices and demand for clean carbon-free energy continue to grow and no single technology exists that can begin to supplement global energy demands in a clean manner. Myriad renewable energy technologies must be developed and honed and solar power is already in the mix, especially in regions of the world with high levels of incident sunlight, like the South-Western United States and Australia. Today, solar power accounts for approximately 0.01% of electricity used in the United States. The most aggressive growth projections put electricity from solar at only 2-3% by the year 2030[1], this is however a significant increase and not one that should deter development of novel photovoltaic devices. In 2005 the solar industry shipped over $700 million in cells and modules, a 40% increase over 2004[2].

HEMJ space solar cells are being tested and implemented in high-concentration photovoltaic systems for utility scale installments, this seems to be the only realistic terrestrial landing market for space solar cells. No other terrestrial solar market has demonstrated such remarkable returns-to-scale, it is for this reason I have chosen to investigate implementing HEMJ with SiGe technology here.

Problem Statement

The following document seeks to (i) understand current markets for high-efficiency multi-junction (HEMJ) solar cells, (ii) speculate on near-term proliferation of HEMJ solar cells in novel applications and energy markets and (iii) project market share attainability for HEMJ solar cells grown on compositionally graded SiGe substrates being developed at the Massachusetts Institute of Technology by Professor Eugene Fitzgerald and at the Ohio State University by Professor Steven Ringel.

Document Overview

To understand the place of HEMJ solar cells in today's energy market, it is first necessary to understand the underlying science and technology. In Chapter 2 I will begin by introducing the basic physical phenomena that make the photovoltaic effect possible and then explain typical solar cell functionality, module assembly and array building. Upon gaining an understanding of how photons interact with materials to produce current, it will be straightforward to see how materials properties can critically affect solar cell performance and what technological barriers have been overcome to advance HEMJ cells grown on Si technology to their current state.

After understanding the science and technology we can begin to dissect the historical and projected markets for HEMJ solar cells. The current satellite power and terrestrial high-concentration photovoltaic (HCPV) markets are explored in chapters 3 & 4 respectively. In these chapters I discuss which specific performance enhancements are relevant and why cost can be reduced by a shift to SiGe. Due to the stronghold HEMJ solar cells currently have on the satellite market, estimating the extent to which an improved technology can capture the market is rather straightforward. In the current atmosphere of concern over global climate change and the future of meeting evolving and expanding global energy demands, interest in diversifying our renewable energy resources is at an all time high. Projecting this concern and interest into future markets for HEMJ solar cells is an important aspect of the market analysis.

Chapter 5 concludes the document with a cost model for HEMJ cells grown on both Ge and Si. Recommendations for future analysis and possible business models for taking this technology to the market place are also put forth. Economic implications are summarized and market penetration strategies are discussed.

Chapter 2—The Science and Technology

Introduction

Photovoltaic devices convert light energy to electrical energy. Two basic functions must be filled for a material to be photovoltaic, it must (i) absorb a photon and create an electron hole ($e^{-}e^{+}$) pair and (ii) separate the charges to conductive contacts to create current. If a photovoltaic absorbs photons emitted by the sun, then it is a solar cell. The type of solar cell that we are interested in makes use of one or a few p-n junctions. The simplest way to understand the functionality of a p-n junction solar cell is the simple case of the Si single junction PV. Imagine two regions of Si, in direct contact, the first being p-type doped and the second being n-type doped. We know that the region of contact acts as a diode, that is, promotes current flow in one direction. When a photon is incident on the Si, it can (i) reflect, (ii) pass straight through the Si (low-energy photons) or (iii) be absorbed by the material and (a) produce heat if it's energy is less than the electrical band gap or (b) create an $e^{-}e^{+}$ pair if it's energy is greater than that of the electrical band gap energy of Si (multiple $e^{-}e^{+}$ pairs may be created if the energy of the incident photon is greater than any integer multiple of band gap energy).

Because the p-n diode in the depletion region is responsible for determining current flow, it is the minority carriers on either side of the diode that are important (that is, the carrier which experiences the concentration gradient). In the P-type doped region, the minority carrier is the electron and in the N-type doped region, the minority carrier is the hole. It is important that minority carriers live long enough to reach a conductive contact before recombining with a hole, one can imagine a scenario where many photons are absorbed to create many $e^{-}e^{+}$ pairs, but they don't live long enough to create current and you are therefore left with a poor photovoltaic, from an efficiency standpoint.

A single p-n junction solar cell limits the percentage of incident photons that may be absorbed by the material. If multiple materials were stacked atop one another, a multiple p-n junction solar cell could be created. This multi-junction photovoltaic, if optimized, could then absorb a greater percentage of incident photons. The theoretical maximum percentage of photons incident on the device that create e—e+ pairs is known as the quantum efficiency, and represents the maximum efficiency of a solar cell. The quantum efficiency of a two-junction solar cell is greater than that of a single-junction cell, similarly a three-junction cell has greater quantum efficiency than a two-junction cell, and so forth. The working figure of merit, however, is the efficiency defined by power output by the device per power incident on the device. For single junction Si solar cells, efficiencies are approximately 10-15%, for more advanced III-V multi-junction devices, efficiencies can be as high as 30%.

Space Solar Cell Technology

Historical Background and Market Disruption

In 1958 the Vanguard I space satellite used a small (less than one watt) array to power its radios. Later that year, Explorer III, Vanguard II, and Sputnik-3 were launched with PV-powered systems on board. Since these initial successes, solar power has been the industry standard for onboard power supplies. Today, satellite arrays produce tens of kilowatts of peak power at efficiencies of ~25%. Flat panel (as opposed to concentrated) arrays have always been used for satellite power, however, material type has evolved from single-junction Si cells to III-V HEMJ cells produced primarily by Spectrolab, a division of the Boeing Corporation.

The first satellite using III-V compound solar technology was launched in the late 1980's, and the first HEMJ satellite was launched in the mid 1990's. For a number of reasons, which are addressed in this chapter, HEMJ cells have overwhelmingly become the choice for satellite power.

Clayton Christensen uses the term disruptive innovation to describe a technological innovation that eventually renders an existing technology obsolete[3]. Examples of disruptive innovations include the semiconductor transistor, which replaced vacuum tubes and the fuel-injector, which replaced the carburetor. It could similarly be argued that the HEMJ solar cell made the single-junction Si flat-panel solar cell obsolete in the satellite power industry. The single largest contributing factor to this sea change was a drastic increase in W/m^2 and W/kg that accompanied the increase in efficiency. Cell cost was certainly not the driving force, however, end launch cost, power availability and payload availability were.

Multi-Junction Solar Cells

For decades, III-V compound semiconductors have been used as photovoltaic materials. Many compounds may be used to create multi-junction solar cells, but special attention must be paid to matching the current produced in each layer. This may be understood by considering the geometry of a multi-junction solar cell; p-n junctions are stacked in such a way as to absorb photons as they pass through the materials. The highest energy photons are absorbed at the top of the cell by the material with the largest band gap, photons with energy lower than the band gap are allowed to pass through the high band gap material to be absorbed deeper in the structure by a lower band gap material. This geometry lends well to maximizing efficiency, but also requires cells to be connected in series. Because the junctions are connected in series, special attention must be paid to current-matching each junction. The least-producing junction in the monolithic stack limits current produced by the device, extra current produced in other junctions tends to bottle neck and manifest as heat, degrading overall cell performance.

Ideally, a multi-junction solar cell would have a high band gap top layer, followed by consecutive layers with band gaps that decrease by the same incremental amount at each step, so as to make sure a similar amount of light is absorbed at each layer. This can be quite hard to do, especially when considering lattice matching between layers. If the lattice constants at adjacent layers differ by more than ~1-2%, dislocations arise to accommodate misfit, and dislocations degrade the lifetime of minority-carriers. To get an idea of the complexity of choosing materials for multi-junction cells, figure 1 shows the relationship between band gap and lattice constant in several compound semiconductors.

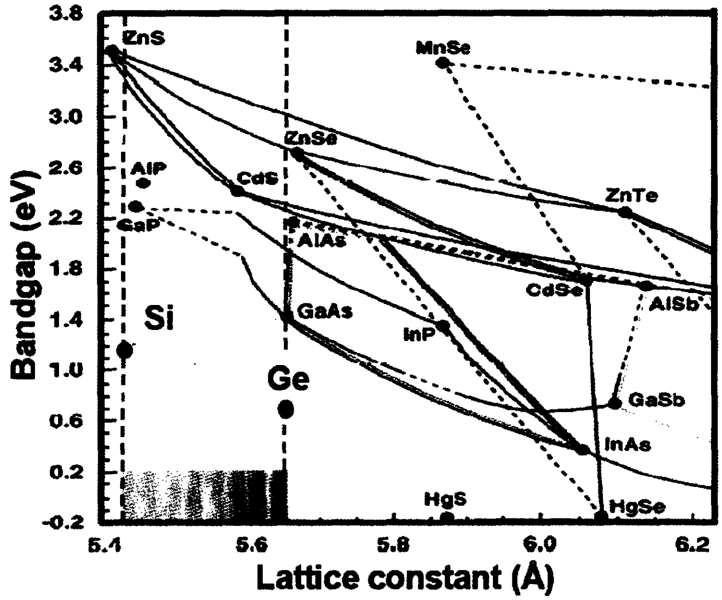
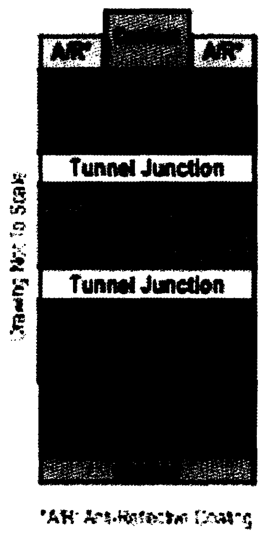


Figure 1, Bandgap versus lattice constant for common semiconductor compounds, (Ringel, 2005)

Currently, strictly for lattice matching reasons, III-V solar cells are produced on a Germanium (Ge) substrate. Germanium is a good substrate option as far as performance is concerned, but not ideal for robust, lightweight, low-cost III-V solar cells that might penetrate markets other than specific space sectors. A shift from Ge to Si substrates would be ideal, and has in fact been a driving force in some solar cell research for over a decade.[4] It should be noted that in the case of building III-V solar cells on Ge, there are a limited number of compounds that may be used which closely match the lattice constant of Ge; however, for a SiGe substrate, many more compounds may be considered because the lattice constant may be adjusted to lie anywhere between that of Si and that of Ge.

Spectrolab Inc. currently produces III-V HEMJ solar cells for both space and terrestrial applications. Spectrolab Inc. sells triple-junction space solar cells capable of beginning-of-life (BOL) operating efficiencies of 28.3%, and triple-junction terrestrial concentrator cells capable of 35% efficiencies under ~400 suns. Below is a basic diagram of the triple-junction cells produced by Spectrolab, courtesy of the Spectrolab, Inc. website.



Multi-Junction Solar Cells Grown on SiGe

There exist significant materials properties advantages to moving to a Si substrate; these advantages are outlined in the table below.

Material Property	Si	Ge
Density (g/cm^3)	2.33	5.32
Thermal Conductivity (W/Cm*C)	1.3	0.58
Tensile Strength (Mpa)	700-7000	40-95

The materials advantages to using a Si based substrate are, lower mass density, better mechanical strength, increased thermal conductivity, wider materials availability and scalability of Si substrate.[5] Thermal conductivity is especially important for terrestrial applications, as will be shown in Chapter 4; mass density and tensile strength, however, are more relevant to the space applications.

Eugene Fitzgerald of MIT and Steven Ringel of OSU have been developing single and dual junction III-V compound solar cells built on engineered SiGe substrates. Further advances are needed, but no great obstacle exists; at this point it is an issue of fine-tuning, rapid commercialization would drastically increase performance due to more precise manufacturing and standardized procedures.

Obstacles to Growing III-V Compounds on SiGe

The 4% lattice mismatch between III-V compounds and Si has until recently degraded cell performance beyond usefulness.[6] Misfit is defined by the difference between the lattice constant of a substrate and an overgrown layer, divided by the lattice constant of a substrate, $f = \frac{a_{si} - a_{oi}}{a_{si}}$. This misfit may be accommodated simply by strain if the overgrown layer is below a critical thickness defined by the energetic of the lattice and dislocation network, or by strain and dislocations in the overgrown layer is above this critical thickness. Figure 2 schematically shows how these dislocations manifest.

A high density of dislocations seriously degrades the lifetime of minority carriers, making solar cell efficiencies low. For instance, homoepitaxially grown GaAs doped in the low 10^{17} (cm^{-3}) range exhibits minority carrier lifetimes of 10-20ns, whereas heteroepitaxially grown GaAs on Si exhibit minority carrier lifetimes in the 2-3ns range (for threading dislocation densities of $\sim 10^7 cm^{-2}$).[7]

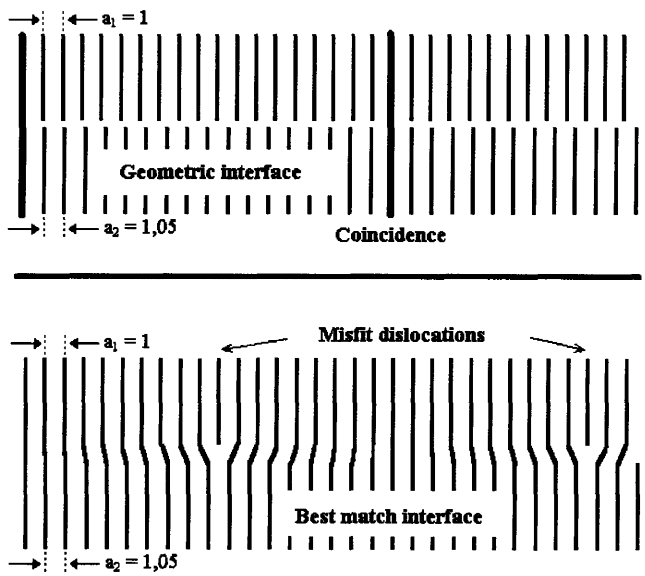


Figure 2. above diagram shows how misfit is defined, below diagram shows how misfit is accommodated with atomic half planes.

Solution

It has been shown my Fitzgerald et al.[8] that by growing compositionally graded, $Si_{1-x}Ge_x$ layers on top of a Si substrate in two steps with a chemical-mechanical polishing step in between, dislocation densities in the low 10^6 cm^{-2} range can be attained, with corresponding minority carrier lifetimes of 9ns. By UHV/CVD it is possible to grow a compositionally graded buffer layer on top of a Si substrate such that within the span of about 12 μm it is possible to have a linearly changing composition from 100% Si to 100% Ge. By using this compositionally graded buffer layer, a virtual Ge substrate is created on which III-V compounds may be grown with lattice matching as close as 0.1%. Growth of thick graded layers alone is enough to accommodate the 4% lattice misfit between Si and Ge; however, to achieve low threading dislocation densities another step is required. If the growth process is modified so that a chemical-mechanical polishing step is implemented at the 50% growth mark, layers can be kept closer to the critical thickness for nucleation, avoiding overwhelming densities of threading-dislocations. This important realization is responsible for the successful monolithic integration of III-V compound solar cells on engineered Si substrates; it is this technology that is the focus of the cost and market analysis that follows.

Performance of III-V/SiGe to Date

In 1998 Fitzgerald et. al. demonstrated low TDD, $\sim 10^{-6}/cm^3$ in fully relaxed Ge layers grown on SiGe compositionally graded buffer layers on Si[9]. This was the first step towards achieving high minority-carrier lifetimes necessary for high-efficiency solar cells built on Si. Further work required developing growth methodologies for III-V compounds on virtual Ge substrates. Single-junction GaAs/SiGe/Si and dual-junction InGaP/GaAs/SiGe/Si have been demonstrated in the past few years, Fitzgerald et. al. Have reported record minority-carrier lifetimes for III-V/Si and record open-circuit voltages for solar cells grown on Si.[10] [11]

By varying the composition of the top layer of the virtual Ge substrate, effectively any lattice constant between that of Ge and that of Si can be achieved. This creates the possibility to grow defect free layers of many compounds on top of the Ge substrate. Figure 1[12] above indicates how Ge or GaAs substrates, which have similar lattice constants, can be replaced by engineered SiGe/Si substrates. Essentially all lattice constants between Si and G are attainable.

Single and dual-junction solar cells built on SiGe/Si have demonstrated record-breaking open-circuit voltages. This is due to low levels of recombination in the depletion region associated with high TDDs, which allows for high minority carrier lifetimes. The performance of the single-junction cell, GaAs/SiGe/Si, cannot be expected to improve significantly; however, the single-junction experiment should be viewed as more of a stepping stone towards multi-junction devices. With this said, the single-junction cell did exhibit the highest open-circuit voltage and energy conversion efficiency ever recorded for a III-V/Si device and rivals even the most advanced single-junction cells on the market today in terms of efficiency, despite lacking the years of hyperfine development which high-efficiency Si cells have undergone.

Current matching between the InGaP/GaAs junction and the GaAs/SiGe junction has so far limited the dual-junction InGaP/GaAs/SiGe/Si[13] solar cells. This is a "good" problem however, because it indicates that the major hurdle has been overcome; that is, poor performance caused by high TDDs. Further tuning of composition of the sub-cells should drastically increase performance. This research indicates that with enough development, III-V/SiGe multi-junction solar cells can match the electronic performance the state-of-the-art III-V/Ge technology within a few years. Matching performance while retaining the materials properties benefits of Si would certainly be disruptive to all applications making use of III-V/Ge multi-junction technologies.

Chapter 3—The Space Market

Overview

The expensive nature of III-V multi-junction solar cells has historically limited their application to niche markets where performance trumps cost, namely, solar power for satellites; although I will be exploring terrestrial markets, the mature satellite industry should not be overlooked as it may be an appropriate market entry focal point. It is important to first delineate various portions of the market where III-V/Ge currently has a stronghold and hence where III-V/Si could surely gain market share due to improved materials properties and cost savings due to improved mass density. There are many different space applications with varying power requirements. Deep space missions, for instance, typically have minimal use for photovoltaics due to the long distance from the sun and hence very small photon fluxes. Exploratory missions in our own solar system tend to have irregular, custom solar power requirements that render solar cell demand hard to predict.

Orbital missions such as GPS systems, telecommunications, weather satellites and so on have very predictable, and ever increasing, power requirements. With 863[14] known satellites in Earth orbits as of July 1, 2007, the market is real and growing at ~10%/year. Before continuing to breakdown the orbital market it is necessary to understand the various orbits and their associated performance requirements. LEO (low-Earth orbit), MEO (mid-Earth orbit) and GEO (geosynchronous orbit) are all defined in the following section.

Orbital Environments[15]

There are a number of factors that play into the types of solar power that is available to any particular satellite. Because satellites are not protected by Earth's atmosphere, they encounter high levels of Van-Allen belt radiations as well as solar flare radiation. This radiation can be highly damaging to photovoltaic devices, and needs to be considered when designing solar power arrays for satellites of various orbits and various degrees of exposure to radiation.

Thermal cycling is also orbit dependent. The performance of photovoltaic devices is highly dependent on temperature and fluctuation in temperature. Deep missions tend to be very cold but constant, LEO missions tend to be warmer but fluctuate with higher frequency.

The cost of sending a satellite to LEO is much less than the cost of sending a satellite to MEO or GEO, and hence, lifetime expectations of satellites varying according to orbit. LEO orbits tend to be shorter-term and place a higher priority on beginning-of-life (BOL) efficiencies, whereas, GEO missions place a higher priority on a well-quantified and predictable EOL efficiency. This is because GEO missions design satellites to remain in operation 15 years from launch, when solar panels have significantly degraded.

Launch costs are very high for all orbits, and therefore, high-efficiency is valued above all. There is a high premium on specific power, from both the mass and area perspectives; that is, W/kg and W/m^2 are the most important figures of merit in the satellite power business. As will be shown later in this chapter, even an order of magnitude difference in solar cell price does not overcome the value of superior specific power.

The following is a list of orbital environmental conditions taken from Sheila Baileys article in *Progress in Photovoltaics.*[16]

LEO

LEO missions (150-1000miles):

- Encounter low levels of radiation damage
- Encounter ≈6000 thermal cycles per year (moving in and out of Earth's shadow)
- Require lifetimes of several months to a few years
- Place high priority on beginning-of-life (BOL) efficiency
- Are primarily used for weather, observation/climate change, military and telecommunication satellites
- Launch costs ≈$12,000 1998USD/kg

MEO

MEO missions (1000-22,000miles):

- Encounter high radiation damage (only know radiation combatant is shielding)
- Encounter many thermal cycles
- Require limited lifetimes
- Are primarily used for scientific gathering purposes
- Telecommunication market would greatly benefit from expanding to MEO (greater global coverage with fewer satellites)

GEO

GEO Missions (>23,000miles):

- Encounter significant electron radiation from trapped electrons in magnetosphere
- Encounter fewer, and less intense, thermal cycles (≈100 cycles per year)
- See constant illumination
- Require longest lifetime of any orbit (+12yrs)
- Place high importance on end-of-life (EOL) efficiency
- Launch costs ≈$70,000 1998USD/kg

Performance Requirements

Since proving their ability to withstand the harsh orbital environments, while also providing the best area and mass efficiencies, multi-junction III-V solar cells have become the industry standard for all but the most energy efficient space missions. After III-V single junction cells proved their superiority to Si cells in the mid 1980's, they quickly gained >70% of the market share and since the first III-V multi-junction powered satellite launched in 1997, the industry has witnessed a similar trend. Today, Spectrolab, a division of Boeing, has production capacity for III-V multi-junction space solar cells of ≈600kW/yr, or enough to power about 50 new satellites per year.[17]

As was stated by Peter Iles, and as is obvious from launch costs, high-efficiency and lightweight are the two most important price-to-performance metrics. High-efficiency solar cells necessitate less area, which translates into increased maneuverability, less complication in deploying arrays once in orbit, and less fuel demand. Lightweight cells clearly decrease launch costs by a significant factor. Si is not only half the mass density of Ge; it is also mechanically stronger, requiring less material for deposition of III-V compound layers. Further exploration of cost-savings based on mechanical strength and decreased mass density will follow in the cost considerations section of this chapter.

There are a number of distinct parts of the space solar market and each has unique requirements for performance. There are, however, a few general features that any space mission will encounter: the AMO unfiltered solar spectrum encountered in orbit around earth is 30-40% more intense than on earth's surface, thermal cycling is more intense and can range over as much as 200°C, and there exist severe radiation conditions due to Solar winds and electrons and protons in the Van Allen belt. The extent to which various space missions experience these effects can be quite different. Although many different types of space missions with differing performance requirements exist, by focusing primarily LEO, MEO and GEO orbits we can cover most of the commercial sector and the bulk of demand[18].

In general, as outlined by Peter A. Iles, space missions require the following aspects of solar cell performance:

(i) High conversion efficiency, because the area available is usually limited;

(ii) Light-weight, particularly as solar arrays become lighter;

(iii) Tolerance to possible degradation by localized effects, including charged particle radiation bombardment, intense ultraviolet radiation, or electrostatic charging;

(iv) Robust performance, especially for the metal contacts, to withstand the environmental factors in

(iii), mechanical stresses during rocket launching, and often from repeated cycling over temperature ranges of around 200°C;

(v) High reliability is particularly important because of the key role PV power plays in overall mission success. Low costs for cells/arrays are less important than for terrestrial applications, because the balance of systems costs are much higher for space power systems, and high reliability is most important.[19]

Power

From the Union of Concerned Scientist satellite database, which updates quarterly and tracks all known orbiting satellites, it can be seen that most satellites being launched today require 3-20kW of on-board power. All of this power comes from photovoltaics; fuel is used only for maneuvering the craft. The move to III-V multi-junction cells increased on-board power availability significantly; switching to III-V/SiGe/Si MJ solar cells could once again increase power availability. The array area required for powering a satellite today is approximately half of what it was in the early 1990's. This area reduction decreased launch weight, and increased ease of maneuverability. Switching to III-V/Si would not have the same impact, because area would not be reduced; however, launch weight and array weight reductions would still create significant incentive for switching. III-V/Si would allow for more instruments, greater transmission power and less fuel demand.

Radiation Hardness

Radiation damage leads to decreasing solar cell efficiency with time. Si, although mechanically stronger, is more drastically affected by radiation damage. It is yet unclear how SiGe compositionally graded layers will be affected by radiation. Radiation could potentially increase the density of threading dislocations, which would have negative impacts on efficiency. Currently dual-junction InGaP/GaAs/SiGe/Si cells are being tested on the International Space Station as part of a project known as the *Forward Technology Solar Cell Experiment*[20], which is subjecting a dozen new technologies to the orbital environment. Results have not yet been obtained, and this will certainly be very important to predicting the success of SiGe in space.

It is believed, however, that radiation damage should not be significantly different than current multi-junction cells built on Ge, and in fact, tolerance may be higher in GaAs/SiGe devices. This is evident from terrestrial testing which attempts to mimic radiation in the space environment. Initial experiments show that the SiGe actually increases the mobility of radiation-induced defects, effectively creating a "self-healing" mechanism, which may prove to be of great value in future space solar cells.[21]

Cost Considerations

Although III-V multi-junction solar cells built on a SiGe substrate are inherently cheaper to produce, as is shown in Chapter 5, this fact alone is not enough to penetrate the space market. This is evident from the fact that expensive III-V/Ge cells are currently preferred over high-efficiency Si cells, which are also cheaper. What is seen when considering whether to use high-efficiency multi-junction cells or Si cells, is that the multi-junction cells actually "buy" payload space on the order of $100k per satellite launch.[22] Specific power is important and can leave the satellite operator with the choice of either (i) increasing on-board power or (ii) increase payload by decreasing array weight. In the following analysis of cost due to mass density improvements, it is assumed that III-V multi-junction will at some point be of similar energy efficiency as those currently produced by Spectrolab, Inc. This is a reasonable assumption considering the quantum efficiency limits on both technologies are similar and future development of III-V/SiGe has no significant physical barriers, only time is required.

Weight

Two important metrics lead to decreased solar panel weight, mass density and mechanical strength. The tensile strength of Si is at least an order of magnitude greater than that of Ge. This means Si is much less brittle than Ge, and therefore a robust solar cell may be built on a much thinner Si substrate than Ge substrate. In addition to the increased mechanical strength of Si, it is also approximately half the density of Ge. The combination of these two properties makes for a much lighter solar cell. This, as stated above, leads to significant launch cost savings.

This savings can be illustrated by considering a satellite requiring 20kW of on-board solar power. For this example, assume that the thickness of the III-V multi-junction cell in both Ge and SiGe cases are the same. Also, assume the thickness of the Ge substrate is 140 microns, and the thickness of the SiGe substrate is 110 microns in the thick case (as is the case now) and 75 microns in the thin case (after much development). The BOL efficiency of the state-of-the-art Spectrolab triple-junction solar cell is 28%, and we will assume that after continued research and development, III-V multi-junction on SiGe/Si can achieve a similar efficiency.

The table below outlines launch-weight savings, strictly from reductions in cell weight. Weight savings may in fact be much greater due to expected advancements in radiation hardness that would accompany a SiGe/Si substrate. Increased radiation hardness would require less shielding of solar cells, which is often done with heavy top coatings. Increased radiation hardness would also extend the lifetime of the arrays, making replacement less frequent and spreading out capital costs. This analysis also assumes an Air Mass zero solar spectrum, which would be encountered in orbit. (1366W/m^2)

	Spectrolab UTJ	SiGe/Si Thick	SiGe/Si Thin
Power Needed (kW)	20	20	20
PV Area Required (cm^2)	523,000	523,000	523,000
Substrate Thickness (μm)	140	110	75
Volume (cm^3)	7322	5753	3923
Mass Density (g/cm^3)	5.32	2.33	2.33
Weight (kg)	38.95	13.4	9.14
COST TO LEO (@$12k/kg)	[redacted]	$160,800	[redacted]
COST TO GEO (@$70k/kg)	[redacted]	$938,000	[redacted]

In the above table I have projected the launch costs for three solar cells. The first is the Spectrolab Ultra Triple-Junction cell currently in production, the second is a realistic substrate thickness for an III-V multi-junction built on a SiGe/Si, and the third is a reasonable thickness goal after continued R&D.

As one can see, there are huge launch cost savings to be had by moving to a SiGe/Si substrate. The difference in launch costs to LEO for Ge and SiGe/Si is at least $400k, and the savings is at least $1.8M for GEO a 20kW GEO mission.

Demand and Growth

In the mid 1990's 80% of satellite power was generated by Si single-junction cells, today 80% of satellite power is generated by III-V multi-junction solar cells. The mid 1990's were a time of rapid growth in the satellite industry, and many vehicles were launched with lower efficiency Si solar cells. Today, many of those mid 1990 satellites are reaching the end of their lifetime and all will be replaced with satellites powered by high-efficiency III-V solar cells.

The period from 2000-2005 exhibited a slowed rate of growth in the satellite industry for the first time in two decades. During this period the market was growing at approximately 10%/year, however, in 2006 the market shot up 32%[23], likely due to the above mentioned mid 1990's vehicles reaching the end of their lifetime. This recent up swing is attributed to renewed interest in GEO missions, which represent much of the growth. 231 GEO missions are planned over the next decade totaling more than $150B in growth, on the other hand, new LEO missions seem to be decreasing in frequency.

Increased interest in GEO missions could be outstanding for III-V/SiGe/Si if expected radiation hardness is demonstrated on the International Space Station. Robust, radiation hard solar cells could potentially have a much greater lifetime—surpassing the 15-20-year limitation of the state-of-the-art. GEO missions put high value on two metrics other than specific power, end-of-life efficiency and lifetime. Both of these values should be improved for III-V/SiGe, making the technology favorable for the most rapidly growing sector of the satellite industry.

Chapter 4—The Terrestrial Market

Overview

The terrestrial market for solar cells is by far the largest, however, the current market is still dominated by Si flat panel PV's, which III-V multi-junction cells cannot compete with on the $/kWh basis. III-V MJ's once again require a niche market; this market is likely to come in the form of high concentration photovoltaics (CPV). The price to performance metric, $/W-installed, can be drastically altered by concentration. Currently the two major III-V MJ manufacturers, EMCORE and Spectrolab, have large and increasing production capacities for concentrator cells.

The United States, although producing much of the needed technology, has been slow to implement CPV systems. The Australian outback has become a testing ground for CPV systems, with many medium scale systems in place and plans for a large, 154MW power plant to come online in the near future. Both Spectrolab and EMCORE have contracts to provide the needed solar cells for this project.

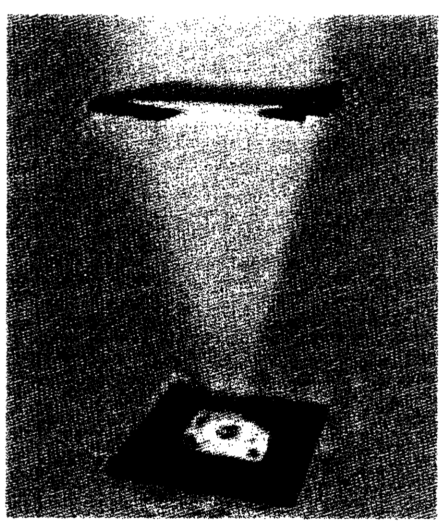
With increasing pressure on state governments to take energy and climate change problems into their own hands, states in the west and southwest regions of the United States are beginning to set goals for solar energy minimums. California, for instance, has agreed to increase its power derived from solar by 3GW by 2017. Arizona, plans to be installing >250MW per year by 2020. In these regions, where yearly sunshine intensity is high and constant, CPV has the potential to gain a large market share.

High Concentration Photovoltaic Systems

Technology

Concentration is one possible means to drastically reduce cost of solar power. The basic idea behind concentrator technologies is that inexpensive concentration lenses may replace solar cell area. The figure below shows a typical concentrator photovoltaic unit. The Fresnel lens concentrates power per area by 100-1000x onto a small high-efficiency cell. Not only does this give more power per unit area, but many materials actually perform better, that is, have higher conversion efficiencies under high concentration.

Concentrating systems, however, are primarily suited for large-scale utility-grade power systems. Because normal incidence on the Fresnel lens is critical for maximizing power output, a 2-axis sun tracking system is needed. This requirement adds a level of complexity, which requires regular maintenance and calibration. For this reason, small-scale systems are cost prohibitive.



There are many different system designs for CPV, although, the modular approach seems to be proving itself superior. This design uses modules composed of 10-20 individual concentrator-solar cell units. Each unit uses a small solar cell, ~1mm^2, onto which two lenses concentrate at levels of 250-1000x. The modules are then fixed together into an array, and the array moves throughout the day to track the sun.

There is much debate about what type of solar cell is move cost effective for CPV. Three big companies use III-V multi-junction space solar cell technologies: Concentrix of Germany, SolFocus of California, and Solar Systems of Australia. Amonix is the other big player in CPV right now, and they are using high-efficiency Si solar cells. Amonix has chosen Si over III-V due to cheaper cost and better thermal conductivity, which is important in their passively cooled systems.

III-V/SiGe would be an ideal replacement of Ge technologies in systems that rely on passive cooling. A material that is better suited to dissipate heat quickly can take on greater levels of solar concentration without detrimental impacts on efficiency. III-V/SiGe technology, therefore, should be focused on development toward high-concentration, >500x, passively cooled systems. There are also benefits to having a material with higher thermal conductivity in an actively cooled system; obviously it is easier to cool a material that is better suited to cool itself, and this could allow for much greater levels of concentration. Passive systems, however, are likely to prove superior from a cost perspective for two reasons; (i) peak conversion efficiencies are usually realized in the 400x concentration range and (ii) passive systems require fewer components for manufacturing, installation and maintenance and are therefore inherently cheaper.

Applications of CPV

There are essentially two applications of CPV technology that seem to be cost-effective in the near-term. The cost of operation and maintenance of CPV systems drastically decreases on a per Watt basis when installations reach into the MW range. Residential systems, which operate on a kW scale, cannot justify the O&M costs, despite drastically increased efficiency and power output per module. The two applications that make sense from a cost perspective are utility-scale installments, either in power-plant form or to supplement the grid during peak-power times during the day.

Power plants will initially be built in remote areas where the cost of electricity is very high. By entering the market in this way CPV companies can provide electricity at a relative discount while at the same time using the system for R&D and realizing returns to scale necessary for bringing the $/W-installed down to a level that could benefit other markets. An example is the Australian outback where electricity is generated by diesel engines. Australia announced a 154MW power plant will be built that will power 45,000 homes and be far and away the largest CPV installment in the world. This system will likely be the true test for CPV and will hopefully jump CPV into the mainstream.

Supplemental power stations are also being considered for CPV applications. In 2006 Pacific Gas & Electric awarded GreenVolts Inc, $120K to develop medium utility-scale systems to supplement the grid during peak usage hours. This niche market is important in places like California that often encounter power shortages and have to import electricity from neighboring states at a high premium. If supplemental energy stations on the scale of 20MW could ease the load during peak daytime hours, this security would be highly valued by residents, governments and electricity companies alike.

Cost Considerations

The cost of CPV will reduce drastically as production volumes increase. Currently system costs are dominated not by the costs of individual solar cells, but instead by assembly, sun tracking, operation and maintenance. There is much room for improvements in these balance-of-system costs that will likely take place before significant emphasis is placed on reducing the cost of the solar cell. Depending on the system being analyzed, solar cell cost seems to range from 5-20% of total system cost. If we take the high end, there is room for great cost reductions by switching to III-V/SiGe, however, if we consider the low end, the savings are negligible.

Consider the for example the Concentrix FLATCON® system, which uses dual-junction high-efficiency solar cells, point-focus Fresnel lenses, and is designed to operate at 500x concentration. In 2005 Concentrix did a thorough cost analysis[24] for the FLATCON®

technology assuming a 20MW/year production line. The results of the cost analysis are summarized in the table below.

Production Cost in $2005/Wp			
Soar cells		$0.60	19.17%
Solar cell assembly		$0.54	17.25%
Lens		$0.21	6.71%
Module assembly		$0.32	10.22%
Specific Module Costs		$1.66	53.04%
Inverter		$0.43	13.74%
Tracker		$0.59	18.85%
Installation		$0.09	2.88%
Tracker and BOS		$1.12	35.78%
Indirect costs		$0.21	6.71%
Security markup	5%	$0.13	4.15%
Total costs		$3.13	100.00%

For the size of the near-term CPV market, I believe the cost model developed by Concentrix best captures the reality. Others have developed models based on much larger production volumes and, in general, they tend to show solar cells as being a much smaller percentage of total system costs.

As can be seen, there are many more components to consider for CPV systems. Lenses, trackers, module assembly and installation are all significant factors. In Chapter 5 I present a cost model, which shows III-V/SiGe multi-junction solar cells would cost approximately 25% of what III-V/Ge multi-junction solar cells cost to produce. Taking this into consideration, solar cell costs in the FLATCON® system could be reduced to $0.15/cell, reducing the system cost to $2.68 and making solar cells a mere 6% of system cost.

Demand and Growth

Although III-V multi-junction solar cells have been used primarily for space applications, terrestrial applications are likely to drive this technology in decades to come. There is much greater overall demand for power in the terrestrial market, and as CPV systems prove cost-, carbon- and politically-effective, the demand for cells on earth will overtake the demand for cells in orbit.

EMCORE and Spectrolab Inc. already have production capacities of over 250MW combined for concentrator solar cells. Germany and Japan have been leading global PV demand for years, however, thanks to the Southwestern and Western United States, the US is likely to soon take over as the leader in world-wide PV demand. Many states in the Western United States have committed to making solar power a primary source of electricity in decades to come. Although subsidies do not exist for CPV technologies, legislation is being put forth to generate incentive. For instance, California recently past legislation to allow residential PV owners to sell more electricity back to the electricity company.

MW's of CPV systems are being tested all around the globe, multi-hundred MW systems are in development and returns to scale are rapidly being realized. Even moderate growth, which is more than likely, would merit investigating a place for III-V/SiGe in CPV.

Chapter 5—Conclusion: A Place for High-Efficiency Solar Cells Grown on SiGe

Economic Implications and Cost Model

Developing a holistic cost model for any emerging technology can be an incredibly difficult process due to the extreme competition between companies that produce needed equipment for manufacturing the various components. This process requires intimate knowledge of manufacturing equipment specifications that are kept secret. Many others have much greater knowledge than I could possibly gain on the timetable of this project, so I have chosen to use Cost-of-Ownership (CoO) models developed by those more proficient than I, those who I have cited below span the spectrum of industry players from consultants to processing equipment manufacturers to solar cell manufacturers. I attempted to adjust for internal bias when considering the numbers I found, and hence, many dollar figures have significant margins of error. I believe, however, that most numbers below are roughly correct and as it turns out, even significant deviation would still show very significant decrease in the cost of production of III-V HEMJ solar cells grown on SiGe.

I have attempted also to estimate costs based on production volumes that would be required to meet combined demand for both the space and terrestrial markets. The industry standard cell size for terrestrial concentrator applications is 1-cm^2, so I will estimate end solar cells costs per cm^2.

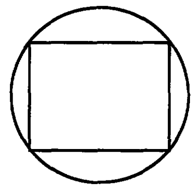
To gain insight into the cost of manufacturing III-V HEMJ solar cells, we must first understand the process of production. The table below illustrates the most cost relevant process steps for production of HEMJ cells on both Ge and SiGe. In reality many more processing steps exist, however, for a simplified cost model such as this, this steps account for the majority of costs. There is one additional processing step for III-V/SiGe; this step is for the production of the SiGe compositionally graded substrate.

III-V/Ge	III-V/SiGe
Purchase 100-mm Ge Wafer	Purchase 200-mm Si Wafer
MOCVD (III-V Deposition)	UHVCVD (SiGe)
	MOCVD (III-V Deposition)
Fabricate Cells	Fabricate Cells

Wafer Cost

The majority of the cost benefit of SiGe comes from the initial purchasing price of the wafer. The average price of a 100-mm Ge wafer is $200-$250, whereas, the average price of a 200-mm Si wafer is $50-$100. These prices were determined by surveying many online wafer sales websites, and in reality, at high purchase volumes significant discounts would probably be given.

Wafers come in, for our purposes, two sizes; 100mm and 200mm. Because photovoltaics are fabricated into rectangular cells, and wafers come in circles, there is a maximum amount of useable area on any given wafer. The maximum useable area can easily be found if you consider that the diagonal of the largest square that can be inscribed in a given circle is the diameter of the circle. This is schematically shown below.



For a 100mm wafer, the maximum useable area is $50cm^2$, for a 200mm wafer, the maximum useable area is $200cm^2$.

UHV/CVD Cost

Once the 200-mm Si wafer has been purchased, the compositionally graded buffer layer must be grown on top of it (This step is not necessary for III-V/Ge). This can be accomplished by either UHV/CVD or LPCVD and the costs are fairly similar. At initial production volumes, the cost per wafer would be \$10-\$15/wafer and would probably fall to \$2-\$5/wafer at higher volumes.[25]

MOCVD Cost

MOCVD is used to epitaxially deposit the III-V compounds on the substrate. This process is highly dependent on the number of wafers that can be placed in the reactor at one time. The platform on which the wafers are placed, known as a susceptor, in a MOCVD chamber is a fixed size so more 100-mm wafers than 200-mm wafers may be placed in the chamber per run. This processing step is cheaper for 100-mm wafers because there is better overall coverage of the susceptor, and the time in the chamber and amount of gas that must be flowed in the process is the same in either case.

The CoO[26] of most MOCVD systems lies somewhere between $500-$1000/run depending on the size of the system. If we take, for example, a susceptor that can hold 13 100-mm wafers or 3 200-mm wafers (this is a fairly standard commercial size), and if we estimate the cost per run to be $750, then the cost per wafer would be ~$60/100-mm or ~$250/200-mm wafer. It is likely that the cost estimate for 200-mm wafers is too conservative, however, to illustrate the overwhelming cost benefit of moving to a 200-mm Si substrate I will use this number.

Fabrication

The cost of fabricating the cells once the III-V compounds have been deposited scales linearly with the number of mask steps, and is pretty much common knowledge. Mask steps cost about $40 each, and for each of these process three mask steps are needed. Fabrication should cost ~$120/wafer, as is pretty much independent of wafer size.

Total Cell Cost

To avoid bias toward the Si technology, I have erred on the side of high cost for 200-mm Si processes steps, and erred on the low side for 100-mm Ge process steps. Despite doing this, it can be seen in the table below that the difference in cost per cell is approximately a factor of four, $8.05 for III-V/Ge cells and $2.28 for III-V/SiGe cells.

Cost ($/wafer)		100-mm Ge	200-mm Si
Wafer		$225.00	$75.00
	Useable Area	50-cm^2	200-cm^2
	Cost Per cm^2	$4.50	$0.25
UHV/CVD		$0.00	$10.00
MOCVD			
	Cost Per Run	$750.00	$750.00
	Wafers Per Run	13	3
	Cost Per Wafer	$57.69	$250.00
Fabrication			
	Cost Per Mask Step	$40.00	$40.00
	Number of Mask Steps	3	3
	Cost Per Wafer	$120	$120
1-cm^2 Cells/Wafer		50	200
Cost/Cell		**$8.05**	**$2.28**

Solar Cell Demand

Space

Spectrolab and EMCORE are the primary providers of III-V MJ solar cells for satellite power. The satellite industry requires approximately 1MW of additional space solar power per year. Spectrolab alone is capable of producing 600kW, making them by far the largest provider. At conversion efficiencies of around 26% for advanced triple junction cells that are dominating new satellite solar arrays, and considering that all of the above mentioned companies are building on top of 100mm Ge wafers, to meet the 1MW demand, the industry must produce about 500,000 100mm wafers per year.

Of these 500,000 wafers per year, Spectrolab must be producing approximately 300,000. Typical 100mm fabs, with and order of magnitude fewer processing steps than a CMOS fab should be able to reach production capacities of around 500,000 wafers per year. This means that for the extraterrestrial demand alone, Spectrolab must be running at nearly full production capacity.

Moving to a Si substrate would mean moving to 200mm wafers, which represents a factor of 4 decrease in the number of wafers that must be processed to meet similar demand. 200mm fabs typically have much higher production capacities, for solar cell production, fab capacity could be as high as 5 million per year. III-V/Si could meet industry demands with 125,0000 wafers per year, which would only be a few percent of production capacity.

Terrestrial

There are three major players in the III-V CPV market, SolFocus, Concentrix and Solar Systems. These three companies only make concentrator systems, and require supply of III-V space solar cells, primarily, from Spectrolab. RWE-Space Solar Power is a

European with production capacity of about 300,000 wafers per year or 130MW of 35% efficient @500x concentration cells. EMCORE and Sharp, two competing space solar cell makers, could also be suppliers to CPV companies, however, seem to choosing to develop their own CPV technologies. Spectrolab has a production capacity of 200MW, or about 420,000 100mm wafers per year. It seems that Spectrolab and RWE-Space Solar Power will in fact be the suppliers of space solar cells for CPV companies.

SolFocus has been rapidly acquiring VC funding for the sole purpose of acquiring a partnership with Spectrolab, which it has done. This was an incredibly perceptive move on the part of SolFocus, and illustrates the future harsh competition for space cells. With this partnership, along with an order from Solar Systems of Australia for 500,000 cells, or 11MW, and extraterrestrial demand probably has Spectrolab producing at maximum capacity.

Thin film and crystalline Si technologies currently cost around $4/W installed. SolFocus technology, in prototype for costs around $8/W, but is projected to come down to $2/W in 2007 when mass production begins. They project that cost will be as low as $0.35/W when production reaches 1Gw/year. $0.35/W would be very competitive with almost any commercial utility.

Based on numbers released by leading CPV companies, it is safe to assume 200MW/year is an upper limit on current terrestrial concentrator demand. At this demand, approximately 350,000 wafers would need to be produced each year. Once again, this is near capacity for a 100mm fab.

Total

Total wafer production for these two niche markets totals about 800,000 wafers per year. This number could be cut to about 200,000 wafers per year if the industry switched to 200mm technology. This switch would allow production capacities to skyrocket, and allow companies like SolFocus to realize their GW per year production very soon (the threshold for $0.35/W).

If GW/year production is the goal of companies like SolFocus, Concentrix, and Solar Systems, the III-V space solar cell producers of the world will need to drastically increase production capacities. Although this may mean building many 100mm fabs, the demand could be met with far fewer 200mm fabs. A single 200mm fab, could in theory, produce about 10GW per year.

Closing Remarks

A Market Entry Strategy

A strategic market entry for III-V multi-junction solar cells grown on Si should take into account the strengths of the technology over the state-of-the-art, use these strengths as leverage and then expand into other markets when high production volumes have been reached. This should be accomplished by entering the mature space market first, and then expanding into terrestrial markets in due time. The benefits of this entry would be two-fold; it would give III-V on Si producers time to realize returns-to-scale while simultaneously allowing the CPV market to mature.

The space market is ready for a new generation of solar cells and can foot the bill if solar cell costs are initially higher. As was shown by Edward Gaddy[27], the demand for increased performance far outweighs the demand for cheap solar cells in the space market. III-V multi-junction cells were initially chosen over high-efficiency Si despite the factor of 5 increase in cost[28]. Though the performance differences between III-V/Si and III-V/Ge are not as drastic as the performance difference between III-V/Ge and high-efficiency SI, the decreased weight will take higher precedence. In his research Gaddy finds that for LEO missions, decreased weight of solar arrays buy additional payload at a price of $57,000 to $141,000 per kilogram. This would by far make up for any additional cost incurred by using a new technology, such as III-V/Si, which has yet to realize cost reductions due to high production volumes.

After obtaining significant market share in space, terrestrial markets could be considered. The demand for III-V/Si in space markets would essentially pay for the ramp-up of production volumes. At these higher production volumes, solar cell costs on the order of those presented in the above cost model, could be realized. These lower cell costs would likely translate into significant total system cost reduction, however, cost reductions will likely be realized in other aspects of the system in the near-term. O&M, assembly and tracking will most likely be areas where returns-to-scale will naturally occur as large-scale systems come online around the globe. After these balance-of-system costs settle, improvements in solar cell performance and cost will be more important to total system cost. This is why entering the space market first, buys time for both III-V/Si and CPV technologies to mature to a point where a mutually symbiotic relationship could exist.

Who Will Take III-V/Si to Market

There are a number of ways in which III-V/Si may make it to the market place. The current owners of the technology will face the decision in the near future and will most likely choose to sell their technology to one of the current industry players. The other options would be to, (i) produce high quality 200-mm SiGe epi-ready wafers to solar cell producers or (ii) produce III-V multi-junction solar cells on SiGe/Si substrates, themselves.

These latter two options are not ideal for a number of reasons, least of which, is industry experience. Companies like Spectrolab and EMCORE have been researching, developing and manufacturing space solar cells for years, and already have hundreds of millions of dollars of infrastructure in place. These companies would be much better suited to quickly realize the returns-to-scale that make III-V/Si so appealing from a cost perspective.

From an intellectual property standpoint, there is only a finite timeline on which this technology can be kept private. It would be interesting to find out how long it would take a startup company to be profitable, and producing solar cells at maximum production volume. Comparing this timeline with the lifetime of the intellectual property may indicate that building a company from scratch based on this technology would be very risky.

The strategy for taking this technology to market that will most likely prove to be most beneficial to all involved, is selling to a current industry player. Producing high-quality III-V multi-junction solar cells on a 200-mm SiGe/Si wafer, while simultaneously presenting a holistic cost model showing all aspects of cost reductions and a projected end cost-per-wafer could potentially make this technology very appealing to many buyers.

Works Cited

[1] Energy Information Administration, Official Energy Statistics from the US Government

[2] IBID

[3] Christensen, Clayton M.;Raynor, Michael E. (2003). *The Innovator's Solution.* Harvard Business School Press.

[4] S.A. Ringel, R. S. (1998). TOWARD ACHIEVING EFFICIENT III-V SPACE CELLS ON Ge/GeSi/Si WAFERS. *Proc. 2nd World Conference and exhibition on photovoltaic solar energy conversion.* Vienna.

[5] IBID

[6] R. M. Sieg, J. A. (1998). High minority-carrier lifetimes in GaAs grown on low-defect-density Ge/GeSi/Ge Substrates. *Applied Physics Letters* .

[7] IBID

[8] E. A. Fitzgerald, M. T. (1998). Controlling Threading Dislocation Densities in Ge on Si Using Graded Si/Ge Layers and Chemical-Mechanical Polishing. *Applied Physics Letters, Volume 72* (14).

[9] IBID

[10] C. L. Andre, J. A. Carlin, J. J. Boeckl, D. M. Wilt, M. A. Smith, A. J. Pitera, M. L. Lee, E.A. Fitzgerald, and S. A. Ringel, "Investigations of high performance GaAs solar cells Grown on Ge/Si1-xGex/Si substrates", submitted to *IEEE Tran. in Electron Dev. (2004).*

[11] C. L. Andre, A. J. Pitera, M. L. Lee, E. A. Fitzgerald, and S. A. Ringel, "Dual junction In0.49Ga0.51P/GaAs solar cells grown on metamorphic SiGe substrates", submitted to *IEEE Electron Device Lett. (2004).*

[12] Steven A. Ringel, 1. C. (2005). III-V Multi-Junction Materials and Solar Cells on Engineered SiGe/Si Substrates. *Mater. Res. Soc. Symp. Proc. , 836.*

[13] IBID

[14] Database, U. S. (n.d.). *www.ucsusa.org.* Retrieved from Union of Concerned Scientists.

[15] Sheila G. Bailey, D. J. (1998). Space Photovoltaics. *Progress in Photovoltaics* .

[16] IBID
[17] (http://www.boeing.com/defense-space/space/bss/factsheets/spectrolab/spectrolab.html)

[18] Iles, P. A. (2000). Future of Photovoltaics for Space Applications. *Progress in Photovoltaics* .

[19] IBID
[20] R. J. Walters, J.C. Garner, S.N. Larn, J.A. Vazquez, W.R. Braun, R.E. Ruth, J.R. Lorentzen, "Materials on the International Space Station-Forward Technology Solar Cell Experiment, NASA/CP—2005-213431

[21] M. Gonzalez, C. L. Andre, R.J. Walters, S.R. Messenger, J.H. Warner, J.R. Lorentzen, A. J. Pitera, E.A. Fitzgerald, S.A. Ringel, "Deep level defects in proton radiated GaAs grown on metamorphic SiGe/Si substrates", Journal of Applied Physics, 100, 2006

[22] Edward M. Gaddy, "Cost Performance of Multi-Junction, GaAs, and Silicon Solar Cells on Spacecraft", 25th PVSC; May 13-17, 1996; Washington, D.C.

[23] Rebuben F. Richards, Hong Hou, CEUT Emerging Growth Conference, PPT, New York City, July 11, 2007

[24] H. Lerchenmuller, A.W. bett, J. Jaus, G. Willeke, "Cost and Market Perspective for FLATCON®-Systems", http://www.concentrixsolar.de/cms/upload/pdf/SCC_3_Lerchenmueller_2005_04_27_Paper.pdf

[25] Levine, Alan, "Cost of Ownership Challenges in Front-End Thermal Processes" Semiconductor Fabtech, 32nd Edition.

[26] Alan Thompson, W. Kroll, M.A. McKee, R.A. Stall, and P. Zawadzki. "A Cost of Ownership Models for CVD Processes", III-V Reviews, P.20, Vol. 8, No. 3

[27] Edward M. Gaddy, "Cost Performance of Multi-Junction, GaAs, and Silicon Solar Cells on Spacecraft", 25th PVSC; May 13-17, 1996; Washington, D.C.

[28] IBID

References

Database, U. S. (n.d.). *www.ucsusa.org*. Retrieved from Union of Concerned Scientists.

E. A. Fitzgerald, M. T. (1998). Controlling Threading Dislocation Densities in Ge on Si Using Graded Si/Ge Layers and Chemical-Mechanical Polishing. *Applied Physics Letters , Volume 72* (14).

EMCORE Solar. (n.d.). Retrieved from www.emcore.com.

Gunther, E. (2007, May 12). *Gunther Portfolio*. Retrieved from guntherportfolio.blogspot.com.

http://www.boeing.com/defense-space/space/bss/factsheets/spectrolab/spectrolab.html. (n.d.).

Iles, P. A. (2000). Future of Photovoltaics for Space Applications. *Progress in Photovoltaics* .

R. M. Sieg, J. A. (1998). High minority-carrier lifetimes in GaAs grown on low-defect-density Ge/GeSi/Ge Substrates. *Applied Physics Letters* .

S.A. Ringel, R. S. (1998). TOWARD ACHIEVING EFFICIENT III-V SPACE CELLS ON Ge/GeSi/Si WAFERS. *Proc. 2nd World Conference and exhibition on photovoltaic solar energy conversion.* Vienna.

Samar Sinharoy, M. O. (2002). Progress in the Development of Metamorphic III-V Multi-Junction Space Solar Cells. *Progress in Photovoltaics* .

Sheila G. Bailey, D. J. (1998). Space Photovoltaics. *Progress in Photovoltaics* .

SolFocus. (n.d.). Retrieved from www.solfocus.com.

Spectrolab. (n.d.). Retrieved from www.spectrolab.com.

Steven A. Ringel, 1. C. (2005). III-V Multi-Junction Materials and Solar Cells on Engineered SiGe/Si Substrates. *Mater. Res. Soc. Symp. Proc. , 836*.

V.D. Rumyantsev, V. A. (2002). Experimental Installation with High Concentration PV-Modules Using III-V Solar Cells. *PV in Europe--from PV Technology to Energy Solutions.* Rome.

A.W. Bett, B. Burger, F. Dimroth, G. Siefer, H. Lerchenmuuller (2006). High-Concentration PV Using III-V Solar Cells. 4th World Conference on Photovoltaic Energy Conversion. Maui.