Chapter 1

Review of Literature

1.1 Brief History of Energy Consumption:

In the current energy crisis, the search for a viable alternative to hydrocarbons has taken many paths: nuclear, wind, solar, etc. Solar cells provide an attractive form of limitless alternative energy. The placement of solar cells can be unobtrusive and provide not only a source of thermal energy, but electricity. However, the development and implementation of effective photovoltaic cells is hindered by two primary components: cost and efficiency.

In 2008, average worldwide power consumption was 15 TW. Approximately 86 percent of this was derived from the combustion of fossil fuels [1]. Fig 1.1 shows the development of worldwide energy consumption from 1965 to 2008.

The increase in energy consumption is simply a result of the world’s growing population as well as an increase in the average gross domestic product (GDP) per capita [2]. The population is expected to reach 9 billion between 2040 and 2050. In addition, the GDP per capita of a country is known to be directly proportional to its energy consumption per capita [3]. Thus, when taking into account that the average GDP per capita is growing even faster than the population, a drastic increase in the world’s energy demand and consumption seems inevitable in the near future. This prospected increase in energy consumption is one of the biggest challenges faced by our generation. The global petroleum resources are limited.
Some claim that the production of oil has already entered a terminal decline, and that proactive mitigation of an energy crisis might not be possible [4, 5]. More optimistic sources claim that peak oil will happen in 2020 or even later, and that it is possible to maintain a high production of oil several decades from now [6].

Nevertheless, the fossil resources are getting less accessible. Oil is pumped out from deeper wells. Oil rigs are being built in distant areas with hostile climate, and more technologically challenging solutions need to be implemented to withdraw the remaining resources. Not only does this increase the price of production, but also the risk of serious oil spills like the Deepwater Horizon oil spill in the Gulf of Mexico in 2010 [7].

Action needs to be taken to ensure a sustainable energy supply in the future, and there is already a strong ongoing political effort to allocate energy consumption away
from fossil fuels. In addition, there has been much focus on the role of fossil fuels on global warming.

1.2 Resources of Renewable Energy

According to the Intergovernmental Panel on Climate Change (IPCC) most of the observed temperature increase since the middle of the 20th century was very likely caused by increasing concentrations of greenhouse gases in the atmosphere resulting from human activity, such as fossil fuel burning and deforestation [8]. This has greatly increased focus on renewable energy both from a scientific and political point of view and several sources of renewable energy are experiencing a significant growth in investments and installed capacity. At the beginning of 2009, the total production capacity of renewable energy was 1.1 TW, with hydroelectric as the dominating source with a share of 83 % [9]. When evaluating the potential of different sources of renewable energy, one needs to take into account the available resources.

1.2.1 Solar energy

Solar energy is, by far, the most abundant energy source. In fig 1.2 the available total energy from different renewable energy sources are represented as the volume of different cubes and compared to the global average consumption. The available solar resources are about 6000 times the total global energy consumption. Thus, less than 0.02 % of the solar resources are sufficient to entirely replace fossil fuels and nuclear power as an energy source.
1.2.2 Average Global insolation and solar power plant

*Fig 1.3* shows worldwide insolation and the possible locations of large solar power plants that in total could provide the total global energy demand. At the end of 2009, the total installed capacity of solar power was 13 GWp [9]. This only accounts for approximately 0.04 % of the total global energy consumption. Still, grid connected photovoltaic (PV). In other words, a doubled installed capacity every second year, see in *Fig 1.4*. To be able to continue this growth, and to make solar power a major supplier in the future energy market, the technology needs to be cost competitive compared to alternative sources of energy 3Wp, or watt-peak, is a measure of the nominal power of a solar cell device under standard illumination and operating conditions; a light intensity of 1000 W/m², with a spectrum similar to sunlight hitting the earth’s surface at latitude 35°N in the summer (air mass 1.5) and a temperature of 25°C electricity has been the fastest growing energy source over the last ten years, with an average annual increase of about 42 % [9].
20 years ago, solar cells were still regarded as a niche market and interesting only in off-grid and space applications areas where other sources of power either were unavailable or too expensive. Today, the situation is completely changed.

Increased cell performance at reduced production and installation costs have cut down energy pay-back times for some solar modules to close to one year [10-11]. With a further reduction in solar electricity prices, the technology will become cost-competitive in yet larger markets. In a recent roadmap on solar power from the International Energy Agency (IEA), PV is projected to provide 5% of global electricity consumption in 2030, rising to 11% in 2050, corresponding to a installed capacity of more than 3 TWp [12]. Today, 80% of the installed capacity of solar electric comes from crystalline silicon solar
Despite being a poor optical absorber, silicon is by far the most commonly used base material for solar cells. The combination of abundance, availability, non-toxicity, and convenient physical properties make silicon a natural choice of material for PV also in the future [14].

Fig 1.4: Total installed capacity of solar electricity from 1996 to 2008 (BP statistical review of world energy 2009)[1].

The relatively young PV industry also has benefited greatly from the huge knowledge base of the microelectronic industry. Still, a necessary road ahead also for silicon solar cells is a further reduction in the price of solar electricity.

This can be done either by cutting production and installation costs without hampering cell performance, or by increasing power output without increasing production and installation costs. One very promising high-efficiency solar cell concept is the back-contact back junction (BC-BJ) silicon solar cell [15-16]. This type of cell design
has already been proven to be compatible both with high efficiency and large-scale production [17].

In fact, it is the silicon solar cell concepts that have demonstrated the highest efficiencies both on cell and module level in production [18-19]. Still, several issues need to be solved for BC-BJ silicon solar cells, both to increase the efficiency further towards the theoretical limit [20], and to reduce the production costs. In this thesis several important aspects related to ARC in silicon solar cells are addressed with the aim of both increasing efficiency and reducing costs. This is done through simulations and modeling. Anti-reflection coatings (ARC) have been an important area of study to minimize the reflection from the front surface of the solar cells. ARCs have been optimized theoretically and experimentally on bare or encapsulated cells. Zhao and Green [21] theoretically optimized a number of different ARCs. Much of work has been reported on dual layer anti-reflection coating, where different type of materials were deposited like TiO₂/SiO₂/SiN, by Richards et al. [22], Arturo et al. [23], Bikash et al. [24] etc. The main interest in SiN films is connected with the bulk defect passivation properties of multicrystalline silicon. It is well known fact that SiN PECVD films contain hydrogen which can be released during the thermal treatment passivating the silicon defects. This effect can be enhanced by interaction with Al back contact during a thermal process [25-26].

In recent years extensive research is reported on surface plasmons, which are collective oscillations of the electrons in conductors, for biologic and luminescence applications [27]. However, there has not been extensive study of surface plasmons for commercial silicon solar photovoltaic applications. Catchpole and Pillai [28-29] investigated the suitability of localized surface plasmons on silver nano-particles for
enhancing the absorbance of silicon solar cells in the IR region. They modeled Ag particles as scattering luminescent emitters and made use of the broadened emission peak to facilitate the near band (in IR region) light absorption in a Si thin film. In this thesis, we focus on modeling the metal nano-particle embedded silicon nitride ARC for performance enhancement of commercial silicon solar cells. We investigate use of the extinction properties of embedded metal particles in silicon nitride ARC to reduce the reflections. Based on the standard optical theorem and Maxwell-Garnett effective dielectric function theory [30], model of the new ARC system is simulated. The reflection data generated by simulation is used in PC1D photovoltaic simulation software [31] to show the performance improvement of commercial silicon solar cell.

1.2.3 Chronology of Solar Cell Efficiency

In fig 1.5, we can see the chronology of the efficiencies for different types of solar cell technology.
1.3 The History Highlight of Solar Cells (Photovoltaic Cells)

- **1839** - Alexandre via an electrode in a conductive solution exposed to light Edmond Becquerel observes the photovoltaic effect.

- **1873** - Willoughby Smith finds that selenium shows photoconductivity.

• 1883 - Charles Fritts develops a solar cell using selenium on a thin layer of gold to form a device giving less than 1% efficiency.

• 1887 - Heinrich Hertz investigates ultraviolet light photoconductivity and discovers the photoelectric effect.

• 1887 - James Moser reports dye sensitized photo electrochemical cell.


• 1888-91 - Aleksandr Stoletov creates the first solar cell based on the outer photoelectric effect.

• 1894 - Melvin Severy receives patent US527377, "Solar cell", and US527379, "Solar cell".

• 1897 - Harry Reagan receives patent US588177, "Solar cell".

• 1901 - Philipp von Lenard observes the variation in electron, energy with light frequency.

• 1904 - Wilhelm Hallwachs makes a semiconductor-junction solar cell (copper and copper oxide).

• 1905 - Albert Einstein publishes a paper explaining the photoelectric effect on a quantum basis.

• 1913 - William Coblentz receives US1077219, "Solar cell".

• 1914 - Sven Ason Berglund patents "methods of increasing the capacity of photosensitive cells".

• 1916 - Robert Millikan conducts experiments and proves the photoelectric effect.
• 1918 - Jan Czochralski, a Polish scientist, produces a method to grow single crystals of metal. Decades later, the method is adapted to produce single-crystal silicon.

• 1920s - Solar water-heating systems, utilizing "flat collectors" (or "flat-plate collectors"), relied upon in homes and apartment buildings in Florida and southern California.

• 1932 - Audubert and Stora discover the photovoltaic effect in Cadmium selenide (CdSe), a photovoltaic material still used today.


• 1941 - Russell Ohl files patent US2402662, "Light sensitive device".

• 1948 - Gordon Teal and John Little adapt the Czochralski method of crystal growth to produce single-crystalline germanium and, later, silicon.[33]

• 1950s - Bell Labs produce solar cells for space activities.

• 1953 - Gerald Pearson begins research into lithium-silicon photovoltaic cells.

• 1954 - Bell Labs announces the invention of the first modern silicon solar cell. [34] Shortly afterwards, they are shown at the National Academy of Science Meeting. These cells have about 6% efficiency. The New York Times forecasts that solar cells will eventually lead to a source of "limitless energy of the sun".

• 1955 - Western Electric licences commercial solar cell technologies. Hoffman Electronics-Semiconductor Division creates a 2% efficient commercial solar cell for $25/cell or $1,785/Watt.
• **1957** - AT&T assignors (Gerald L. Pearson, Daryl M. Chapin, and Calvin S. Fuller) receive patent US2780765, "Solar Energy Converting Apparatus". They refer to it as the "solar battery". Hoffman Electronics creates an 8% efficient solar cell.

• **1958** - T. Mandelkorn, U.S. Signal Corps Laboratories, creates n-on-p silicon solar cells, which are more resistant to radiation damage and are better suited for space. Hoffman Electronics creates 9% efficient solar cells. Vanguard I, the first solar powered satellite, was launched with a 0.1W, 100 cm² solar panel.

• **1959** - Hoffman Electronics creates a 10% efficient commercial solar cell, and introduces the use of a grid contact, reducing the cell's resistance.

• **1960** - Hoffman Electronics creates a 14% efficient solar cell.

• **1961** - "Solar Energy in the Developing World" conference is held by the United Nations.

• **1962** - The Telstar communications satellite is powered by solar cells.

• **1963** - Sharp Corporation produces a viable photovoltaic module of silicon solar cells.


• **1967** - Soyuz 1 is the first manned spacecraft to be powered by solar cells

• **1967** - Akira Fujishima discovers the Honda-Fujishima effect which is used for hydrolysis in the photo electrochemical cell.

• **1968** - Roger Riehl introduces the first solar powered wristwatch. [35]
• 1970 - First highly effective GaAs hetero-structure solar cells are created by Zhores Alferov and his team in the USSR.[36-38]

• 1971 - Salyut 1 is powered by solar cells.

• 1973 - Skylab is powered by solar cells.

• 1974 - Florida Solar Energy Center begins.[39]

• 1974 - J. Baldwin, at Integrated Living Systems, co-develops the world's first building (in New Mexico) heated and otherwise powered by solar and wind power exclusively.

• 1976 - David Carlson and Christopher Wronski of RCA Laboratories create first amorphous silicon PV cells, which have an efficiency of 1.1%.

• 1977 - The Solar Energy Research Institute is established at Golden, Colorado.

• 1977 - President Jimmy Carter installs solar panels on the White House and promotes incentives for solar energy systems.

• 1977 - The world production of photovoltaic cells exceeded 500 kW

• 1978 - First solar-powered calculators.[40]

• Late 1970s: the "Energy Crisis"; groundswell of public interest in solar energy use: photovoltaic and active and passive solar, including in architecture and off-grid buildings and home sites.

• 1980 - John Perlin and Ken Butti's landmark book A Golden Thread published, covering 2500 Years of Solar Technology from the Greeks and Romans until the modern day [34].
- **1980** - The Institute of Energy Conversion at University of Delaware develops the first thin film solar cell exceeding 10% efficiency using Cu$_2$S/CdS technology.

- **1983** - Worldwide photovoltaic production exceeds 21.3 megawatts, and sales exceed $250 million.

- **1984** - 30,000 SF Building-Integrated Photovoltaic [BI-PV] Roof completed for the Intercultural Center of Georgetown University. At the time of the 20th Anniversary Journey by Horseback for Peace and Photovoltaics in 2004 it was still generating an average of one MWh daily as it has for twenty years in the dense urban environment of Washington, DC.

- **1985** - 20% efficient silicon cells are created by the Centre for Photovoltaic Engineering at the University of New South Wales.

- **1986** - 'Solar-Voltaic Dome™' patented by Lt. Colonel Richard T. Headrick of Irvine, CA as an efficient architectural configuration for building-integrated photovoltaic’s [BI-PV]; Hesperia, CA field array.

- **1986** - President Ronald Reagan removes solar panels from the White House. [41]

- **1988-1991** AMOCO/Enron used Solarex patents to sue ARCO Solar out of the business of a-Si.

- **1989** - Reflective solar concentrators are first used with solar cells.

- **1990** - The Cathedral of Magdeburg installs solar cells on the roof, marking the first installation on a church in East Germany.

- **1991** - Efficient Photo electrochemical cells are developed; the Dye-sensitized solar cell is invented.
• **1991** - President George H. W. Bush directs the U.S. Department of Energy to establish the National Renewable Energy Laboratory.

• **1992** - University of South Florida fabricates a 15.89-percent efficient thin-film cell

• **1993** - The National Renewable Energy Laboratory's Solar Energy Research Facility is established.

• **1994** - NREL develops a GaInP/GaAs two-terminal concentrator cell (180 suns) which becomes the first solar cell to exceed 30% conversion efficiency.

• **1996** - The National Center for Photovoltaics is established. Graetzel, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland achieves 11% efficient energy conversion with dye-sensitized cells that use a photo electrochemical effect.

• **1999** - Total worldwide installed photovoltaic power reaches 1,000 megawatts.


• **2004** - Kansas Governor Kathleen Sebelius issued a mandate for 1,000MWp renewable electricity in Kansas by 2015 per Executive Order 04-05.

• **2006** - Poly-silicon use in photovoltaics exceeds all other poly-silicon use for the first time.

• **2006** - California Public Utilities Commission approved the California Solar Initiative (CSI), a comprehensive $2.8 billion program that provides incentives toward solar development over 11 years.[42]

• **2006** - New World Record Achieved in Solar Cell Technology - New Solar Cell Breaks the “40 Percent Efficient” Sunlight-to-Electricity Barrier.[43]
• 2007 - The Vatican announced that in order to conserve Earth's resources they would be installing solar panels on some buildings, in "a comprehensive energy project that will pay for itself in a few years".[44]
• 2007 - Google solar panel project begins operation.[45]
• 2007 - University of Delaware claims to achieve new world record in Solar Cell Technology without independent confirmation - 42.8% efficiency.[46]
• 2007 - Nanosolar ships the first commercial printed CIGS, claiming that they will eventually ship for less than $1/Watt. [47] However, the company does not publicly disclose the technical specifications or current selling price of the modules.[48]
• 2008 - New record achieved in solar cell efficiency. Scientists at the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) have set a world record in solar cell efficiency with a photovoltaic device that converts 40.8 percent of the light that hits it into electricity. However, it was only under the concentrated energy of 326 suns that this was achieved. The inverted metamorphic triple-junction solar cell was designed, fabricated and independently measured at NREL.[49]
• 2010 - BP announces the closing of their photovoltaic plant in Maryland, moving all of their manufacturing work to China.[50]
• 2010 - President Barack Obama orders installation of additional solar panels and a solar hot water heater at the White House [51].
• **2011** - Fast-growing factories in China push manufacturing costs down to about $1.25 per watt for silicon photovoltaic modules. Installations double worldwide. [51]

• **2012** - 3D PV-cell with 30% more energy efficiency. [52]

Today, due to the increasing global demands on energy, it is imperative that a renewable energy source be determined, that is cost effective and reliable. Solar cell technology has shown much promise over the years to replace the use of fossil fuels. However, with the current technology, the cost per watt is rather high due to the high cost of manufacturing silicon-based solar cells. The cost per watt can be lowered two ways. Lower the manufacturing cost, or increase the amount of power output for the same cost.

References:


[17] D. De Ceuster, P. Cousins, D. Rose, D. Vicente P. Tipones, and W. Mulligan Low-
cost, high-volume production of >22% efficiency silicon solar cells in 22nd

release, 2008.

[19] Sun power Corp. Sun power announces world-record solar panel with 20.4 percent


Photovolt. Res. Appl. 11, p. 27.


Dual Layer Silicon Nitride Anti-reflection Coating”, Conference Record of 31st

Rosenblum, M. D., 2000, “Aluminum–enhanced PECVD SiNx hydrogenation in
1123.

231–246.


[37] Nanotechnology in energy applications, pdf, p.24

[38] Nobel Lecture by Zhores Alferov, pdf, p.6