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Solar photovoltaic electricity: Current status and future prospects

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Abstract

We review the technical progress made in the past several years in the area of mono- and polycrystalline thin-film photovoltaic (PV) technologies based on Si, III–V, II–VI, and I–III–VI_2 semiconductors, as well as nano-PV. PV electricity is one of the best options for sustainable future energy requirements of the world. At present, the PV market is growing rapidly at an annual rate of 35–40%, with PV production around 10.66 GW in 2009. Si and GaAs monocrystalline solar cell efficiencies are very close to the theoretically predicted maximum values. Mono- and polycrystalline wafer Si solar cells remain the predominant PV technology with module production cost around \$1.50 per peak watt. Thin-film PV was developed as a means of substantially reducing the cost of solar cells. Remarkable progress has been achieved in this field in recent years. CdTe and $Cu(In,Ga)Se_2$ thin-film solar cells demonstrated record efficiencies of 16.5% and almost 20%, respectively. These values are the highest achieved for thin-film solar cells. Production cost of CdTe thin-film modules is presently around \$0.76 per peak watt.

Keywords: Solar; Photovoltaics; Wafer; Thin film; Photovoltaic market; Nanophotovoltaics

1. Introduction

Presently, the world energy consumption is 10 terawatts (TW) per year, and by 2050, it is projected to be about 30 TW. The world will need about 20 TW of non-CO_2 energy to stabilize CO_2 in the atmosphere by mid-century. The simplest scenario to stabilize CO_2 by mid-century is one in which photovoltaics (PV) and other renewables are used for electricity (10 TW), hydrogen for transportation (10 TW), and fossil fuels for residential and industrial heating (10 TW) (Zweibel, 2005). Thus, PV will play a significant role in meeting the world future energy demand. The present is considered as the "tipping point" for PV (Kazmerski, 2006).

The PV effect was discovered in 1839 by Becquerel while studying the effect of light on electrolytic cells. A long period was required to reach sufficiently high efficiency. Solar cells developed rapidly in the 1950s owing to space programs and used on satellites (crystalline Si, or c-Si, solar cells with efficiency of 6–10%). The energy crisis of the 1970s greatly stimulated research and development (R&D) for PV.

Solar cells based on compound semiconductors (III–V and II–VI) were first investigated in the 1960s. At the same time, polycrystalline Si (pc-Si) and thin-film solar cell technologies were developed to provide high production capacity at reduced material consumption and energy input in the fabrication process, and integration in the structure

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of modules by the deposition process and consequently cost reduction for large-scale terrestrial applications.

In this paper, we review the current status of the PV market and recent results on several leading types of solar cells, such as c-Si, pc-Si, and amorphous-Si (a-Si), and III–V, II–VI, and I–III–VI$_2$ semiconductors and their alloys and nano-PV.

2. Efficiency limits

The thermodynamic efficiency of various devices is of wide interest because of the relevance of this parameter for energy conversion. The classic limiting efficiency of a solar cell was analyzed by Shockley and Queisser (1961). They also established a model to describe the electrical behavior of the diode that constitutes the solar cell. This time, the model came from detailed balance arguments and, at first sight, does not give the same results as the standard model. According to Shockley and Queisser (1961), the thermodynamic efficiency for an ideal single-homojunction cell is ~31%. The efficiency of a single-junction device is limited by transmission losses of photons with energies below the bandgap and thermal relaxation of carriers created by photons with energies above the bandgap.

In the classic case, every photon absorbed in a solar cell produces at most one electron–hole pair. Kodolinski et al. (1993) showed quantum efficiencies higher than 1 in the short-wavelength range of a-Si solar cell. This can be explained as an optically induced Auger mechanism: the energy in excess of the bandgap that one of the carriers receives from a high-energy photon is used in a second electron–hole generation. This result has led to the revision of the Shockley–Queisser model of the ideal solar cell, widely accepted as the physical limit of PV conversion.

Several methods have been offered to increase the power conversion efficiency of solar cells, including tandem cells, impurity-band and intermediate-band devices, hot-electron extraction, and carrier multiplication, the so-called "third-generation" PV (Nozik, 2002; Ross and Nozik, 1982; Hanna and Nozik, 2006; Green, 2002; Luque and Marti, 1997; Marti et al., 2006; Schaller and Klimov, 2004, 2006; Tobias and Luque, 2002).

The intermediate-band solar cell (IBSC) relies on the electronic and optical properties of so-called intermediate-band (IB) material, which is characterized by the existence of a collection of energy states located within what would otherwise be the forbidden bandgap of a conventional semiconductor. Normally, energy levels within a semiconductor bandgap are considered as non-radiative recombination centers. However, for ideal operation of the IBSC, these intermediate levels must behave only as radiative recombination centers. Thus, Marti et al. (2006) refer to this collection of levels as an intermediate "band." Radiative recombination can dominate when the wavefunctions of the electrons in the IB are delocalized (i.e., they extend throughout the crystal), as in the conduction and valence bands of conventional semiconductors.

To manufacture an intermediate-band solar cell, the IB material has to be sandwiched between conventional p- and n-type semiconductor emitters that isolate the IB from the contacts. When the device is illuminated, above-bandgap radiation pumps electrons from the valence band (VB) to the conduction band (CB), as in a conventional semiconductor solar cell. In addition, below-bandgap energy photons are able to pump electrons from the VB to the IB and from the IB to the CB. This requires the IB to be partially filled with electrons and implies that the Fermi level has to cross it.

The absorption of below-bandgap energy photons enhances the photocurrent over an ideal single-gap solar cell manufactured from material with the same bandgap E_g. In addition, the carrier population in each band is assumed to be governed by its own quasi-Fermi level (E_{Fc}, E_{Fv}, and E_{Fi} for the quasi-Fermi levels of the conduction, valence, and intermediate bands, respectively). The output voltage is then preserved because it is determined by the quasi-Fermi level split between the conduction and valence bands at the emitters, which is limited by the total bandgap E_g. As a result, the limiting efficiency of the IB solar cell is as high as 63.2% under maximum sun concentration (46,050 suns).

A single-threshold quantum-using device in which the exited carriers thermally equilibrate among themselves, but not with the environment, can convert solar energy with an efficiency approaching that of an infinite-threshold device. Such a hot-carrier flat-plate device operated under typical terrestrial conditions (AM 1.5 illumination, 300 K) can convert solar energy with an efficiency of 66% (Ross and Nozik, 1982). This high efficiency is achieved in part through an unusual inversion, in which the chemical potential of the exited electronic band is below that of the ground band. This negative potential difference reduces radiation losses, permitting a low threshold energy and a high Carnot efficiency, resulting from a high carrier temperature.

Another option to increase the efficiency of solar cells is that of using the carrier multiplication effect. Carrier multiplication, which was first observed in bulk semiconductors in the 1950s, would provide increased power conversion efficiency in the form of increased solar cell photocurrent. The process of inverse Auger recombination or impact ionization, as it is more commonly known, has also been considered as a mechanism to use some of the excess energy of photo-generated carriers to create additional electron–hole pairs in PV devices. When carrier multiplication is active, the effective photon-to-pair generation quantum yield may be greater than 1 for photon energies greater than twice the bandgap. The predicted limiting efficiencies are 44.7% and 85.9% for devices with maximum multiplication under unconcentrated and fully concentrated (blackbody) sunlight, respectively (De Vos and Desoete, 1998). Impact ionization is inefficient in typical bulk semiconductors such as silicon, and calculations show only marginal improvement in efficiency over the Shockley–Queisser limit. Very efficient multiple-exciton generation has been observed in quantum dots made from the