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Thin semiconducting layers as active and passive emitters for thermophotonics and thermophotovoltaics

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Abstract

Thermophotovoltaics involves the photovoltaic conversion by a receiver cell of radiation from an emitter, which could be heated by various sources including sunlight. A prime difference from normal solar photovoltaics is that emitted energy unable to be used by the receiver can, in principle, be recycled allowing high conversion efficiency. Thermophotonics is a recent development of this concept where the emitter is "active", namely a heated diode, increasing the rate of energy transfer for a given emitter temperature and concentrating emission in an energy range more suited for conversion by the receiver. This paper evaluates thin semiconducting layers as emitters for thermophotovoltaics and thermophotonics. It is shown that thermophotonics avoids a major challenge for thermophotovoltaics: the sensitive dependence of system efficiency on the recycling of below bandgap radiation. Possible ways of achieving the high external quantum efficiency light-emitting diode required for thermophotonics are discussed.

1. Introduction

In a thermophotovoltaic (TPV) system, a heated emitter radiates towards a photovoltaic cell, which converts above bandgap radiation to electricity (Fig. 1). The emitter could be heated by concentrated sunlight or by other sources, for example waste heat from high temperature industrial processes. Below bandgap light is reflected to the heated emitter, helping to maintain its temperature. The recycling of below bandgap energy means that very high efficiencies are thermodynamically possible. Thermophotonics is a recent development of the TPV concept where the emitter is "active", namely a heated diode, increasing the rate of energy transfer for a given emitter temperature and concentrating emission in an energy range more suited for conversion by the receiver (Green, 2001).

The two main approaches to thermophotovoltaics are selective emitters/filters and low bandgap absorbers. With the second approach, very high temperatures are needed to achieve good conversion efficiencies. Selective emitters/filters allow the use of more moderate temperatures. Selective emitters are normally ceramics doped with rare earths such as ytterbium, erbium or holmium. As "passive selective emitters", thin semiconducting layers may provide an alternative offering increased design flexibility to standard rare-earth doped ceramics. The decreased emitter bandgap at high temperature means that for spectral matching the room temperature bandgap of the emitter should be slightly higher than that of the absorber. Low dimensional structures such as quantum wells, superlattices and nanocrystals offer scope for such bandgap control.

A major design issue for thermophotovoltaics is that unless the selective emitter/filter is almost perfect, IR blackbody radiation swamps the luminescent radiation. Thermophotonics avoids this problem through the use of a forward-biased heated diode as the emitter. Under forward bias, the light emitted due to the recombination

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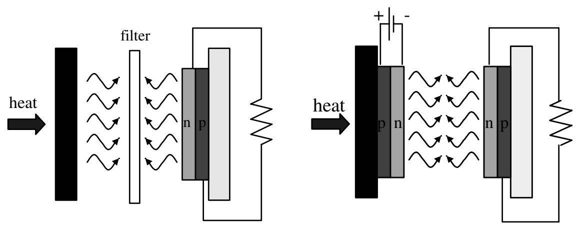

Fig. 1. (a) A thermophotovoltaic system. A heated emitter radiates towards a solar cell attached to a load. Below bandgap radiation is reflected back to the emitter. The system efficiency is sensitively dependent on the efficiency of recycling below bandgap radiation, via a selective emitter or filter. (b) A thermophotonic system. A heated diode radiates towards a solar cell attached to a load. Forward biasing the diode results in narrow band radiation, making a filter unnecessary.

of electron–hole pairs in the heated diode is exponentially enhanced, while thermal emission remains at its zero-bias value. Electron–hole pairs are injected into the heated diode with energy qV (where $qV < E_g$), but recombine to produce luminescent radiation of energy $E_g + kT$. The remaining energy is absorbed by the diode from its junction and contacts to supply the energy balance (Dousmanis et al., 1964). Since the heated diode emits light within an energy, kT, of its bandgap, the luminescent radiation can be converted very efficiently by the receiving cell. If these processes occur with high enough efficiency, there will be a net conversion of heat to electrical energy.

Present experimental work is concentrating on the silicon and GaAs based III–V alloy systems, given the maturity of the associated technology. Experimental work with active emitters has established record light emission efficiencies for silicon diodes (Green et al., 2001). The aim is to repeat this achievement with GaAs based devices. A requirement for thermophotonics is net cooling in the LED, in order that the thermophotonic system can convert heat to electricity. This means that the energy lost through radiation must be larger than the heating due to non-radiative recombination. As a first step towards this goal we are aiming for cooling of a GaAs device via photoluminescence. For GaAs, this requires an external quantum efficiency (EQE) of greater than 97.5%. Gauck et al. (1997) achieved an EQE of 96% using thin GaAs layer and a dome of ZnSe. There is potential to increase this figure through the use of texturing or a dome of very high refractive index material.

2. Emission spectra for thin silicon layers

The emission spectrum of a heated emitter can be predicted from its absorbance, through Kirchoff's law, which states that the spectral absorptance of a body is equal to its spectral emissivity. The absorptance, A, defined as the fraction of incident radiation absorbed by a sample at a given wavelength, is proportional to $(1 - \exp(-\alpha d))$, where α is the absorption coefficient. The steep rise in absorption coefficient at the band edge means that semiconductors can make good selective emitters for thermophotovoltaics, at moderate temperatures. As the temperature increases, the number of free electrons and holes increases due to thermal excitation. Thus at higher temperatures, free carrier absorption increases, as does the inverse process of free carrier emission. Since free carrier emission is only weakly dependent on wavelength, this decreases the selectivity of the emission.

For wavelengths higher than 5 μm the absorption coefficient of rare-earth ceramics is significant, because of vibrational modes of the crystal structures. At temperatures up to 800 K, Si has a lower absorption coefficient at long wavelengths (10 μm) than rare-earth ceramics. The absorption coefficient at long wavelengths is important because even for very good selective emitters, IR radiation dominates the emission spectrum. When combined with a filter to narrow the emission peak, Si may be more suitable as a selective emitter than rare-earth ceramics for moderate-temperature heat source applications.

The reduced bandgap of semiconductors at high temperatures means that emitters (at high temperatures) and absorbers (at low temperatures) made of the same material with the same structure will not be spectrally matched. There is some scope for altering the emission spectrum of a silicon layer to match the bandgap of the absorber. High absorptance (and hence high emittance) requires $\alpha d > 2$, which occurs at higher energies for thinner layers, leading to a shift in the emission peak. Modelled emission spectra for silicon layers showed a small increase in energy of the peak of the luminescent spectrum as layer thickness, d, decreased, from 1.1 eV for a 10 μm layer to 1.15 eV for a 1 μm layer (Fig. 2). The peak does not shift significantly for $d < 1$ μm because for these values of d, A is low over a large energy range, and only changes slowly with energy. Using a planar emitter and a textured absorber also improved spectral matching by increasing the absorptance of the absorber at longer wavelengths. Quantum wells, superlattices and nanocrystals can increase the effective bandgap, and provide further scope for spectral matching.

The modelling also showed a small increase in the emission intensity per unit thickness (I/d) as layer thickness decreased. This was due to the increase of absorptance per unit thickness (A/d) as d decreases (since $A \propto 1 - \exp(-\alpha d) \approx 1$ for large αd). For $\alpha d \ll 1$, A/d is independent of d, so there is no further increase for very thin layers, and no increase for below bandgap emission.

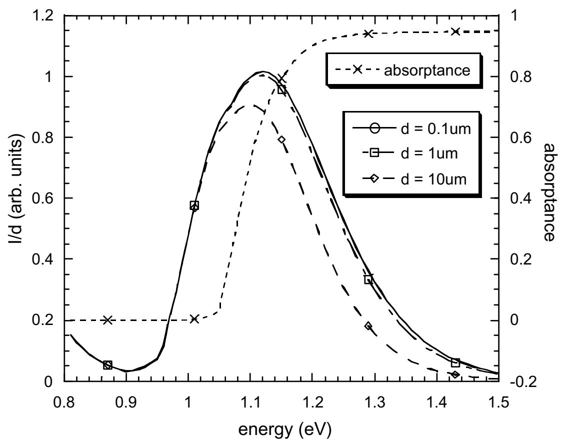

Fig. 2. The emission spectra per unit thickness for Si layers with thicknesses of 0.1, 1 and 10 μm at 600 K. The absorptance of a thick, textured Si absorber (at 300 K) is also shown to indicate the spectral matching.

3. Filters for thermophotovoltaics

One of the most crucial requirements for thermophotovoltaics is suppression or recycling of IR radiation, which cannot be converted to electricity by the absorber. Even for selective emitters such as Si and rare-earth ceramics, very good IR mirrors are required to recycle IR radiation to the emitter and to avoid excessive heating of the absorber. Fig. 3 shows the transmitted spectra for a thin Si emitter with: (a) a highly idealised filter (1% transmittance below the bandgap of a spectrally matched ($E_g = 0.9$ eV) absorber, and 100% transmittance above the bandgap), (b) an applied voltage (i.e. a diode emitter), and (c) without filtering or applied voltage. Without the filter or applied voltage, only 0.05% of the energy is above the bandgap of the absorber. When the highly idealised filter is used still only 5% of the energy is above bandgap. Thermophotonics exponentially increases luminescence, avoiding the problem of excessive IR radiation. With an applied voltage of 0.7 V, 99.7% of the emitted energy is above bandgap. Practical filters are likely to have significantly lower performance than the idealised filter used in these calculations. The difficulties in obtaining a sufficiently good selective emitter, or emitter/filter combination, make thermophotonics an attractive concept, because of the exponential enhancement of the luminescent radiation.

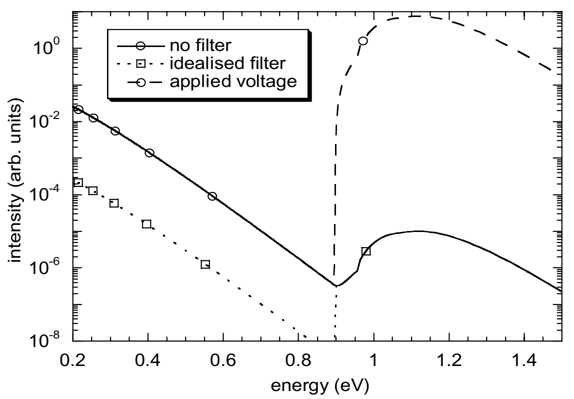

Fig. 3. Emission spectra of a thin Si emitter at 600 K: without filtering or applied voltage, with an idealised filter, and with an applied voltage (for a diode emitter).

4. Implementing thermophotonics

A thermophotonic system consists of a heated forward-biased light-emitting diode (LED), and an unheated solar cell attached to a load (Fig. 1b). In order to achieve net conversion of heat to electricity, a very high external quantum efficiency (EQE) LED is required, so that the LED cools when a voltage is applied. The EQE required depends on the applied voltage V via $\mathrm{EQE}_{\mathrm{req}} > qV/(E_g + kT)$, where q is the electronic charge, E_g is the bandgap of the LED, k is Boltzmann's constant and T is the temperature of the LED. For GaAs with $E_g = 1.4$ eV at an applied voltage of 1.0 V, an EQE of 70% is required. As a first step towards this goal, we are aiming to achieve cooling of an optically pumped structure. In this scheme laser light at the bandgap energy E_g is used to excite electron–hole pairs, which then thermalise with the lattice and recombine, emitting light with energy $E_g + kT$. Thus the required EQE is $E_g/(E_g + kT) \approx 98\%$. Despite the higher EQE required with optical pumping, cooling should be easier to achieve than with electrical pumping, since electrical contacts, which introduce parasitic losses, are not needed.

Radiative recombination within GaAs is very efficient, and internal quantum efficiencies (IQEs) of 99.7% have been achieved (Schnitzer et al., 1993). The main difficulty with achieving high EQEs is extraction of the emitted light, due to the high refractive index of semiconductors ($n = 3.5$ for GaAs). This means that only light emitted within 16° of the normal can escape from a wafer of GaAs into air, which is 2% of the total radiation emitted within the GaAs. The rest of the radiation is totally internally reflected within the GaAs, and eventually reabsorbed. This is the reason that commercial LEDs generally have efficiencies of less than 2%.

There is a range of ways of increasing the extraction efficiency, including a dome of transparent high refractive index material, texturing the surface, and photon recycling (see Fig. 4). A dome of high index material increases the range of angles that can escape from the GaAs. For example, a dome of ZnSe ($n = 2.5$) increases

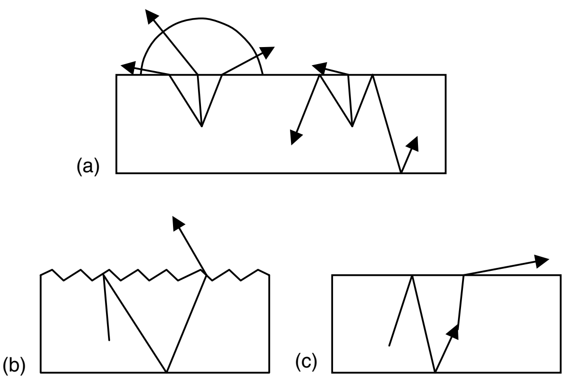

Fig. 4. (a) A high index dome increases the range of angles of photons that can escape from the semiconductor. (b) Texturing randomises the direction of the light each time it strikes the textured surface of the semiconductor, allowing it an additional chance to escape. (c) Photon recycling randomises the direction of the photon by absorption and re-emission. A very high internal quantum efficiency is required for photon recycling to be effective.

the critical angle to 45°, which is 30% of the emitted radiation. (If a thin layer of GaAs is used with a rear reflector, the escape cone doubles, to 60% of the emitted radiation.) The photons that escape the GaAs strike the surface of the dome at 90°, and hence are transmitted. This approach has been used by Gauck et al. (1997), who achieved a 96% EQE with an optically pumped structure, and came very close to achieving cooling.

Texturing and photon recycling work by randomising the direction of the light, allowing it another chance to escape. With texturing, the direction of the photon is randomised every time it strikes the textured surface, with a 2% chance each time to find the escape cone. This approach has been used to achieve an EQE of 40% with a GaAs diode (Windisch et al., 2000).

With high quality material, photon recycling can be a significant factor. When a totally internally reflected photon is re-absorbed by the GaAs, the high IQE of the GaAs means that there is a high probability that a photon will be re-emitted. Since the photon is re-emitted in a random direction, this provides another 2% chance to fall within the escape cone. This phenomenon was exploited by Schnitzer et al. to obtain an EQE of 72% with an optically pumped structure (Schnitzer et al., 1993). To obtain this efficiency, each photon had to reincarnated about 25 times.

5. Conclusions

In this paper, thin semiconducting layers were evaluated as emitters for thermophotovoltaics and thermophotonics. It was shown that thermophotovoltaic system efficiency is very sensitively dependent on the recycling of below bandgap radiation. Even with a very good filter, the IR blackbody radiation swamps the luminescent radiation for a thin Si emitter. This problem will also occur with rare-earth selective emitters. With thermophotonics, the problem is avoided, because an applied voltage exponentially enhances the luminescent radiation, while the thermal radiation remains unchanged. To implement thermophotonics, a high external quantum efficiency LED is required. This could be achieved by improving the extraction of light from a radiatively efficient semiconductor such as GaAs.

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