SOLAR CELL AND ITS APPLICATION

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OUTLINE OF THE PRESENTATION

❖ Objective of the work.

❖ A brief introduction to Solar Cell technology

❖ Challenges in solar cell technology.

❖ The concept of quantum dot solar cells.

❖ What are quantum dots?

   ❑ Size–dependent band gap tunability in quantum dots

   ❑ Multiple exciton generation (MEG) in quantum dots.

❖ Theory of the efficiency as a function of band gap characteristics of quantum dot absorbers.

❖ Results and discussion.

❖ Conclusion.
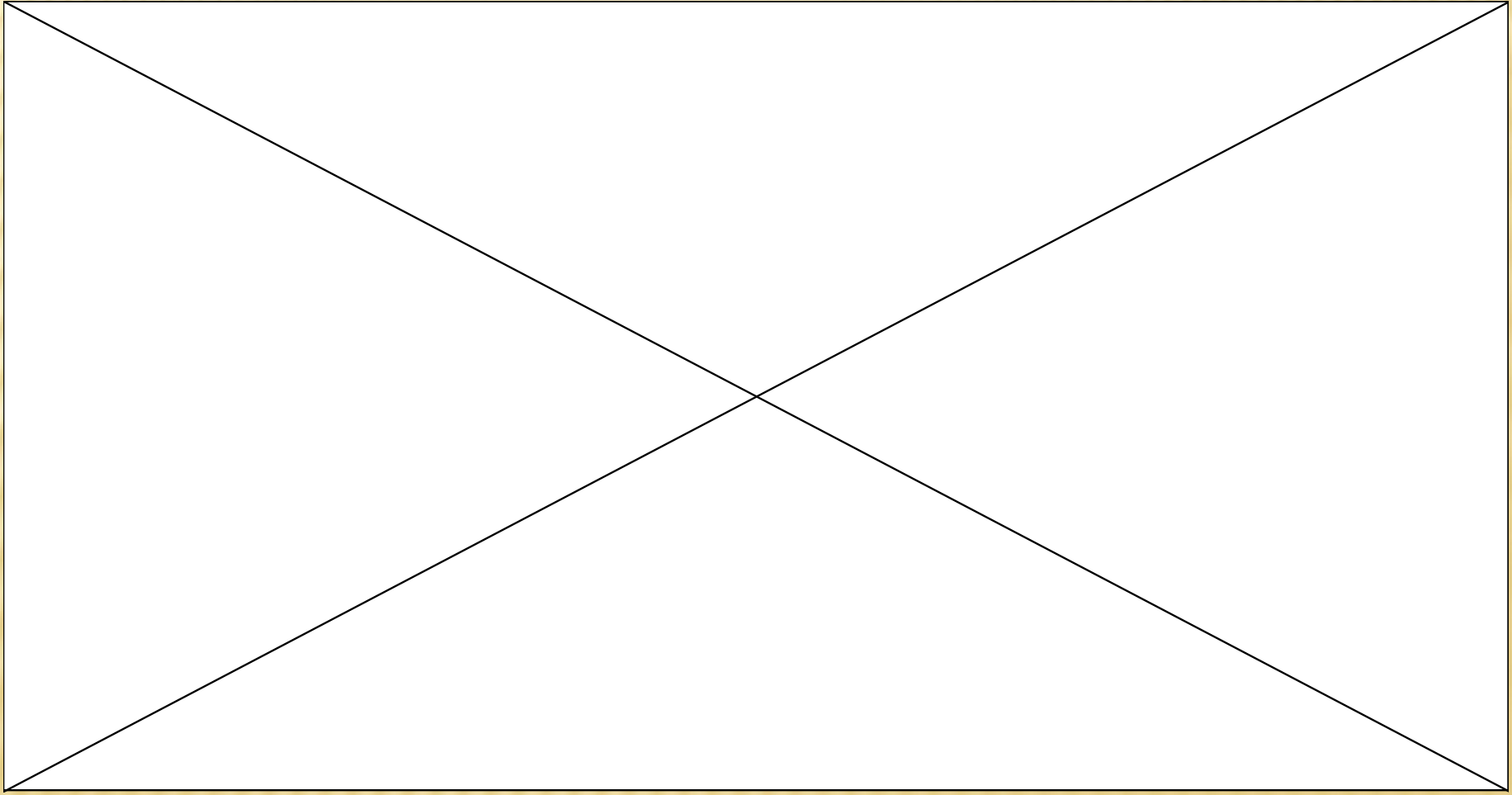
OBJECTIVE OF THE WORK

❖ The objective of the work is to show that the inclusion of quantum dots in a conventional solar cell (quantum dot solar cell) can increase the efficiency of a solar cell from 30% to 42% by minimizing thermalization and transmission losses in the cell.

INTRODUCTION TO SOLAR CELL TECHNOLOGY

❖ Solar energy is clean, free and inexhaustible and is plentifully available on our planet in comparison with other energy sources.

❖ It is estimated that the amount of solar energy radiated by the sun in a day (1.34×10^{31} J/day) can satisfy the world's energy requirements in a whole year.

❖ Mankind has continually been refining the methods of harnessing this energy through solar cell technology. A solar cell is a device that converts solar energy directly into electrical energy, making it easily convertible to other forms of energies. Figure 1 is a schematic representation of the modern type of a single junction semiconductor solar cell.
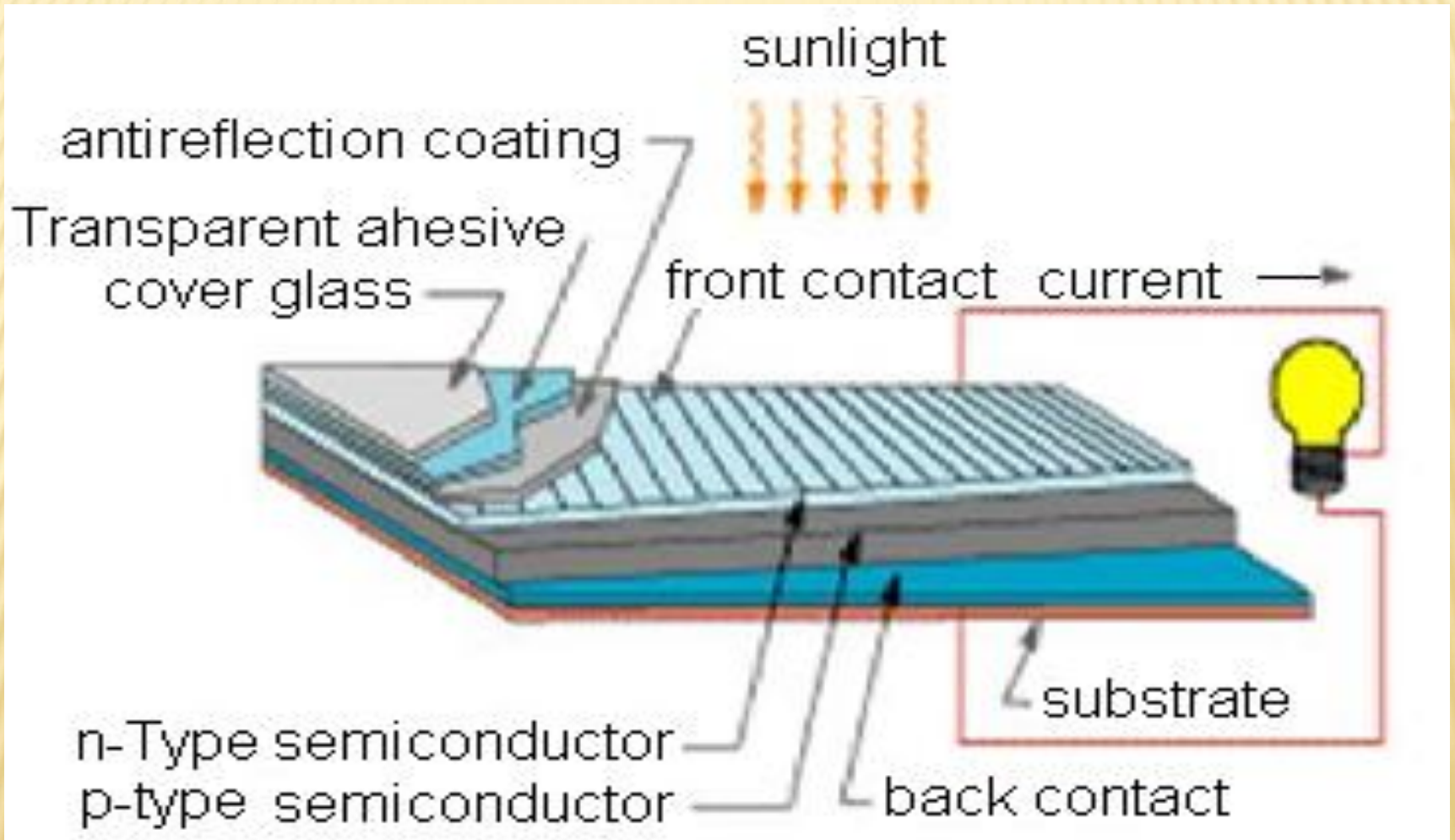
Fig 1: Schematic diagram of a semiconductor solar cell

CHALLENGES IN SOLAR CELL TECHNOLOGY

❖Solar cell technology is beset with two major challenges today and these challenges have limited their widespread use for several decades.

> (i) The cost of manufacturing solar cell components is very high making it very expensive.

> (ii)The operational efficiency (the percentage of converted solar power) is 30% which is extremely low, (Shockley and Queisser 1961).

The energy losses that produce the low efficiency come from the following sources :

> (i) Transmission losses ~20%
> (ii) Thermalization losses ~30%
> (iii)Recombination of charge carriers

(iv) Reflection of sunlight at the solar cell
    surface

(v) Resistance and temperature effects

❖The last two losses have been fairly addressed and so the low efficiency is mainly due to the first three losses.

❖This research is an attempt to minimize transmission and thermalization losses using quantum dots.

❖These two losses (transmission and thermalization) occur due to mismatch between the energies of photons in sunlight (0.5–3.5) eV and the band gaps (1.0–1.7) eV of bulk semiconductors or semiconductor compounds used in the manufacture of solar cells.

❖ Only photons with energies equal to the material's band gap are efficiently utilized to generate electrical energy.

❖ Photons with energies less than the band gap are unable to activate the solar cell and hence are not utilized at all to generate electrical energy (transmission loss).

❖ Photons having energies greater than the band gap are utilized to generate electrical energy, but the excess band gap energy is lost as heat (thermalization loss).

❖ Transmission losses occur in bulk semiconductors because these materials have fixed band gaps that cannot be changed to match the wide range of wavelengths in sunlight. Figure 2 illustrates the absorption threshold of some semiconductor materials.
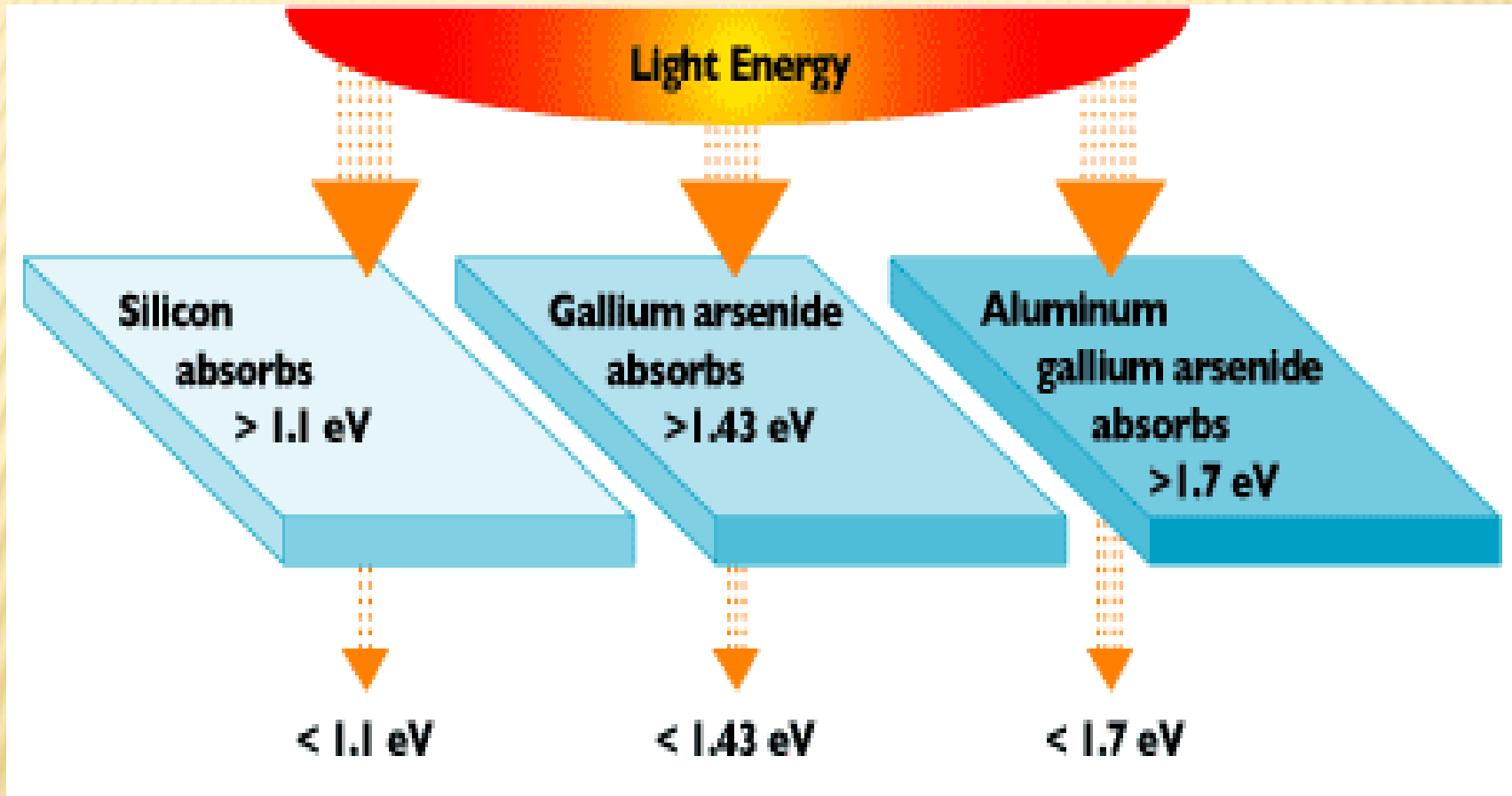
Fig 2: Absorption threshold of different semiconductor materials

❖Thermalization is the loss of excess band gap energy of a photon as heat. The excess band gap energy of a photon becomes kinetic energy of the photo generated electron.

❖Thermalization losses occur as a result of many sequential hot electron-phonon scattering events due to the 3-dimensional nature of bulk semiconductor or semiconductor compounds.

❖Then the quasi continuous energy levels in both bands allow the emission of a large number of phonons in the sub pico second time scale.

❖This process is much faster than any other competing process in bulk semiconductors and is illustrated in fig 3.
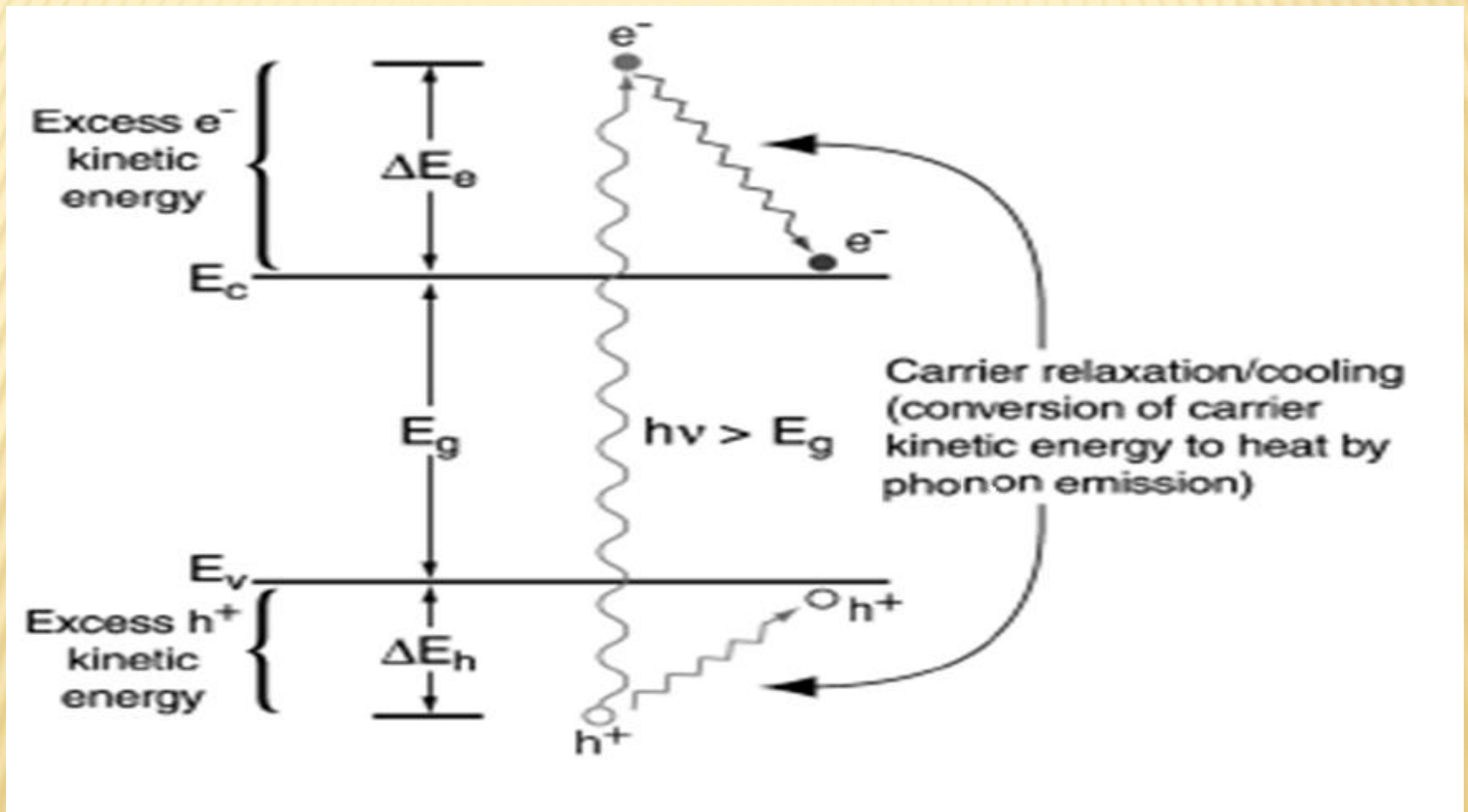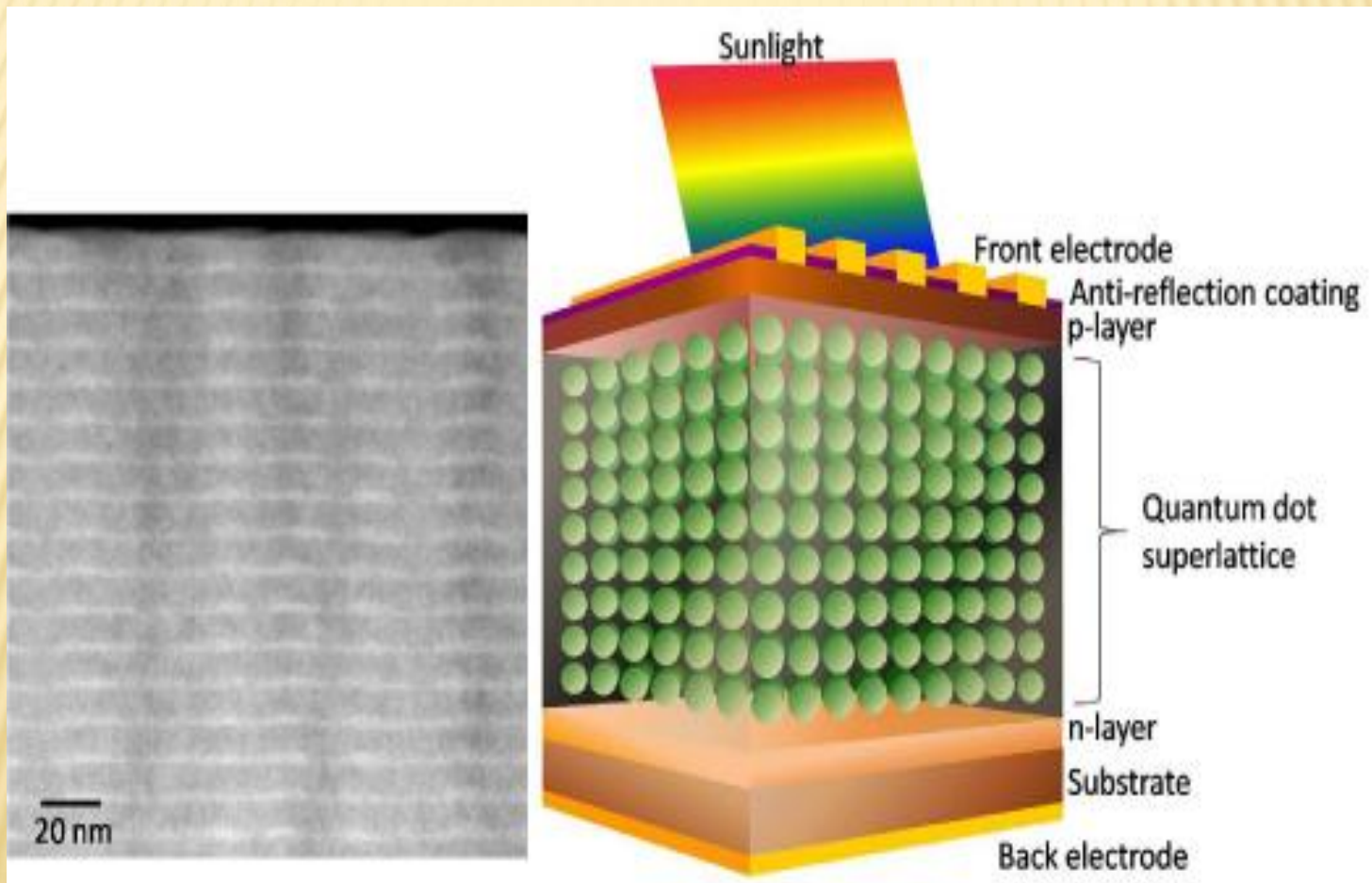
Fig 3: Hot carrier relaxation / cooling in semiconductor solar cell

SOLAR CELL WITH QUANTUM DOT

QUANTUM DOT SOLAR CELL CONCEPT

❖ The solution to these two problem requires a solar cell material :

(i) whose band gap can be easily tuned to match the wide range of wavelengths in the solar spectrum.

(ii) which is zero-dimensional and has discrete energy levels in both bands so as to suppress the occurrence of thermalization and instead, allow the excess band gap energy to be utilized to generate other electron-hole pairs.

Such a material is expected to be a totally quantized semiconductor structure or a quantum dot.

WHAT ARE QUANTUM DOTS

❖A quantum dot is a fabricated semiconductor nano-particle which contains a variable number of electrons confined in all three spatial dimensions.

❖It contain fewer number of atoms due to its small size and the electron de-Broglie wavelength is comparable to the dimensions of the dot hence the interaction between the atomic levels produce quantized energy levels both in the valence and conduction bands.

❖The discrete energy levels are similar to those of naturally occurring atoms and hence a quantum dot can be described as an artificial atom.

❖Figure 4 shows a comparison of the energy levels of bulk CdSe semiconductor and CdSe quantum dot.
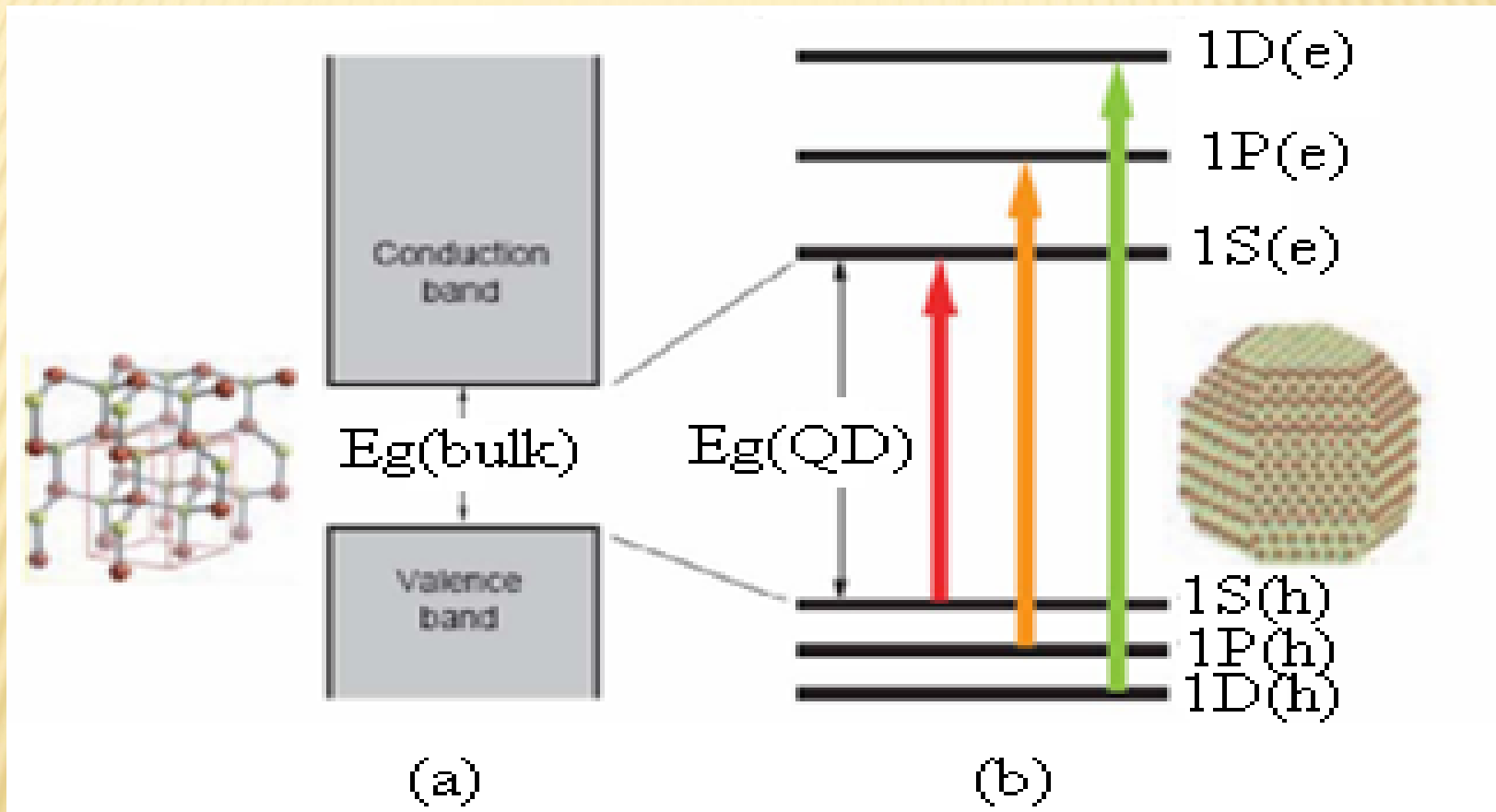
Fig 4 (a) CdSe bulk semiconductor and (b) CdSe quantum dot

SIZE-DEPENDENT BAND GAP TUNABILITY OF QUANTUM DOTS

❖The band gap of a quantum dot, (Brus 1984) can be calculated approximately from

$$E_{\min} = \frac{\hbar^2 \pi^2}{2R^2}\left[\frac{1}{m_e^*} + \frac{1}{m_h^*}\right] - \frac{1.8\,e^2}{\varepsilon R} - 0.25 E_{Ryd} \qquad (1)$$

R is the radius of the quantum dot and E_{Ryd} is the bulk exciton binding energy in meV.

❖The first term is the quantum localization which shifts the energy gap to higher energies as R^{-2}.

❖The second term is the coulomb term which shifts the energy gap to lower energies as R^{-1}.

SIZE-DEPENDENT BAND GAP TUNABILITY OF QUANTUM DOTS cont'd

❖ Consequently, the band gap increases in energy as the diameter of a quantum dot is decreased and vice versa.

❖ Hence the wavelength absorption or emission properties of a quantum dot depend on the size of the dot.

❖ A small quantum dot has a wide band gap and absorbs high energy photons (shorter wavelengths or bluer light), while a larger dot has a narrow band gap and absorbs low energy photons (longer wavelengths or redder light) even if dots are of the same semiconductor compound.

❖ A quantum dot can also be described as an electromagnetic absorber or emitter with tunable band gap. This is a useful property in minimizing transmission losses and is illustrated in figure 5
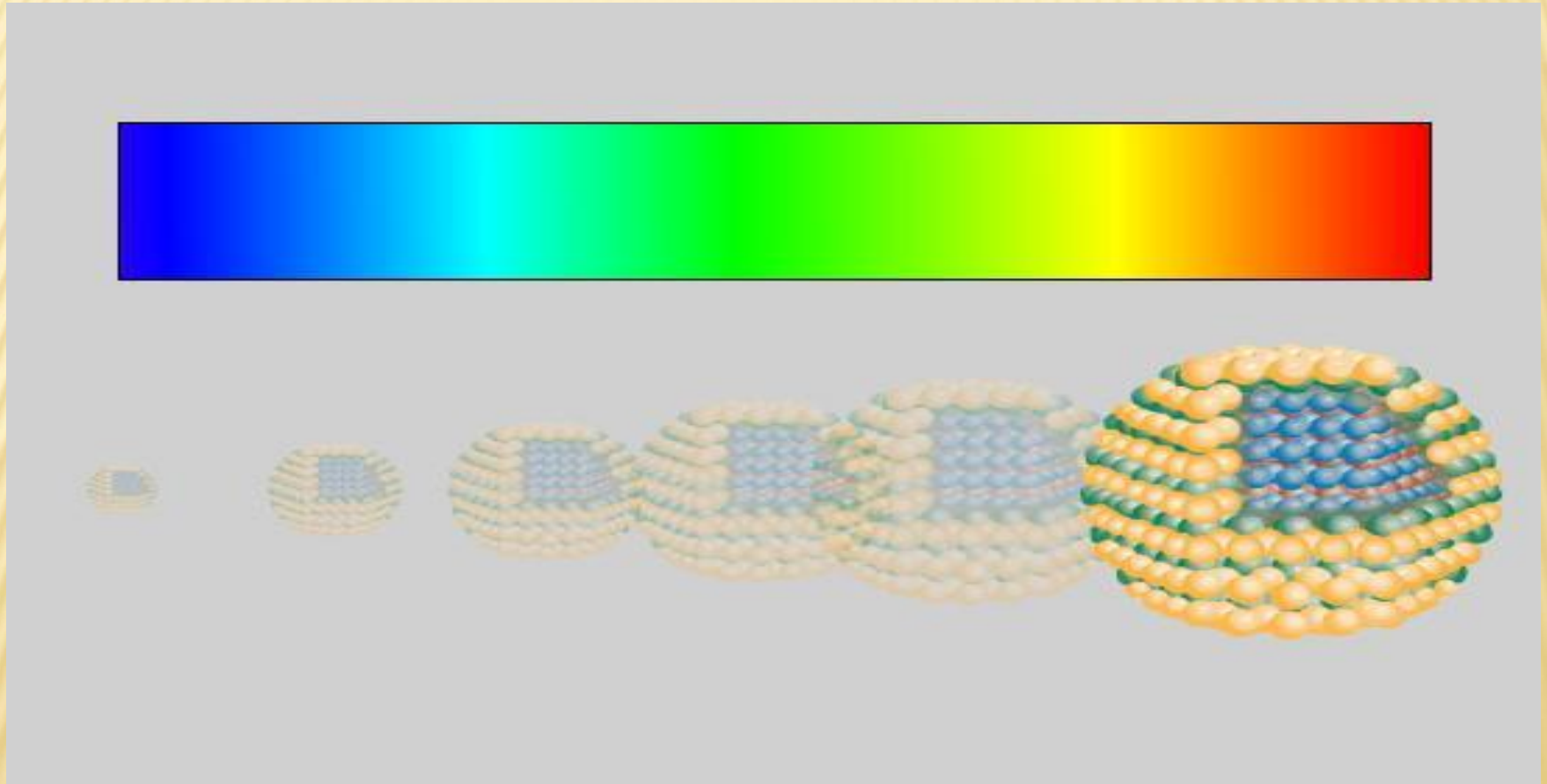
Fig 5: Matching of the output colour and the quantum dot size.

MULTIPLE EXCITON GENERATION (MEG) IN QUANTUM DOTS

- (Nozik ,2000), predicted that the small size of a quantum dot, coupled with its quantum confinement could lead to multiple exciton generation or impact-ionization

- Impact-ionization is a process by which the interaction between a photon with excess band gap energy and an electron in a quantum dot produce several electron hole pairs or excitons.

- This occurs because in a quantum dot, the reduced dimensionality also implies a reduction in the number of electron-phonon scattering, thus suppressing thermalization.

- Instead, the quantum confinement in a quantum dot allows the hot electron to collide with an electron bound to an atom, transferring energy to it and generating another electron-hole pair and so on. This is illustrated in figure 6.
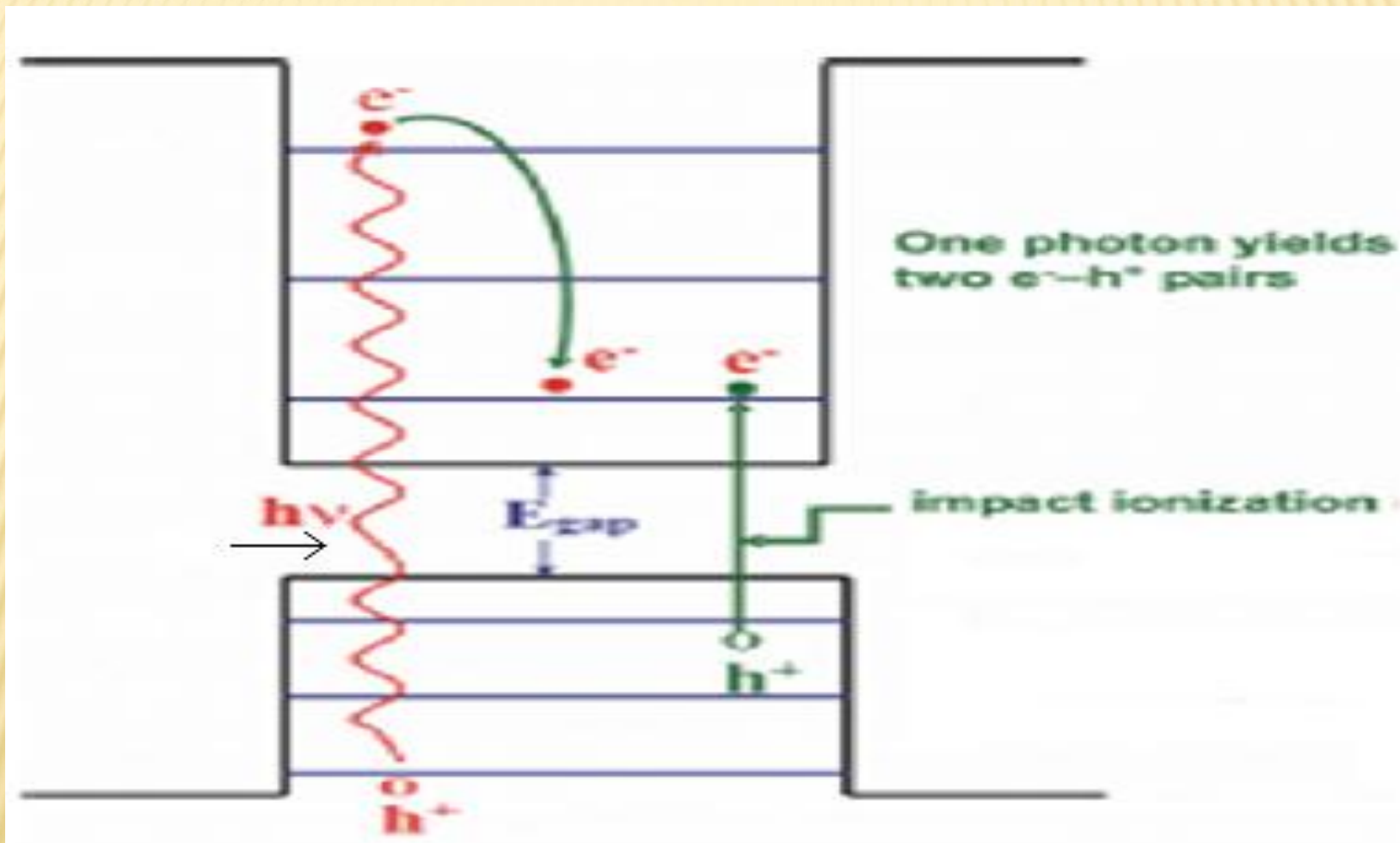
Fig 6: Schematic diagram showing impact ionization yielding two electron-hole pairs in a quantum dot.

❖ Experimental results involving the interaction between high energy photons and several quantum dot materials demonstrate that impact-ionization is practical. Subsequently, three and seven excitons have been produced from PbSe quantum dot (Schaller et al:2004, 2006). There have also been other reports of MEG in PbS, PbTe, CdSe and InAs quantum dots.

❖ A quantum dot is suitable for solar cell material because:

(i) It has a tunable band gap necessary for increased spectral absorption,

(ii) It also allows the onset of multiple exciton generation or impact-ionization by utilizing the excess band gap energy of solar photons.

THE EFFICIENCY–BAND GAP CHARACTERISTICS OF QUANTUM DOT ABSORBERS

❖ The computation is based on the following assumptions:

(i) All photons having energies greater than or equal to the band gap are absorbed.

(ii) Only radiative recombination of charge carriers are allowed.

(iii) The quasi Fermi level separation is given by

$$qV = \mu_C - \mu_V \qquad (2)$$

q is the charge on the electron, V is the voltage across the cell, μ_C and μ_V are the chemical potentials of the conduction and valence bands respectively.

❖ The output current generated in the cell is

$$I(V, E_g) = I_G(E_g) - I_R(V, E_g) \qquad (3)$$

$I_G(E_g)$ is the photogenerated current,

$I_R(V, E_g)$ is the recombination current associated with radiative recombination and

E_g is the absorption threshold or band gap of the material.

$$I_G(E_g) = q \int_{Eg}^{E\max} QY(E)\Gamma(E)dE \qquad (4)$$

$$I_R(V, E_g) = qg \int_{Eg}^{\infty} \frac{QY(E)E^2}{\exp\{[E - qQY(E)V]/kT\} - 1}dE \qquad (5)$$

$E_{\max}$ is the maximum photon energy ~ 4.0eV

q is the electronic charge

k is the Boltzmann's constant

T is the temperature of the solar cell

$\Gamma(E)$ is the photon flux associated with the AM1.5G spectrum.

$QY(E)$ is the quantum yield which allows for the generation and recombination of multiple charge pairs per photon over the appropriate energy range.

$g = 2\pi / c^2 h^3$, c is the speed of light in vacuum and h is Planck's constant. The form of $QY(E)$ is the sum of the Heaviside step function

$$QY(E) = \sum_{m=1}^{M} \theta(E, mE_g) \qquad (6)$$

- M = 1 gives the usual one-photon, one electron without carrier multiplication.

  $M = M_{max} = E_{max}/E_g$ gives the maximum number of excitons.

- Quantum dot absorbers may be denoted by M1, M2 ... Mmax for generating 1,2, ...maximum number of excitons respectively.

- The conversion efficiency of a photovoltaic device is given by

$$\eta_{pv}(V) = I(V)V / P_{in}$$ (7)

- From equations (2), (3), (4), (5), (6) and (7), the graphs of efficiency of quantum dot absorbers as a function of the material's band gap are shown in figure 7.
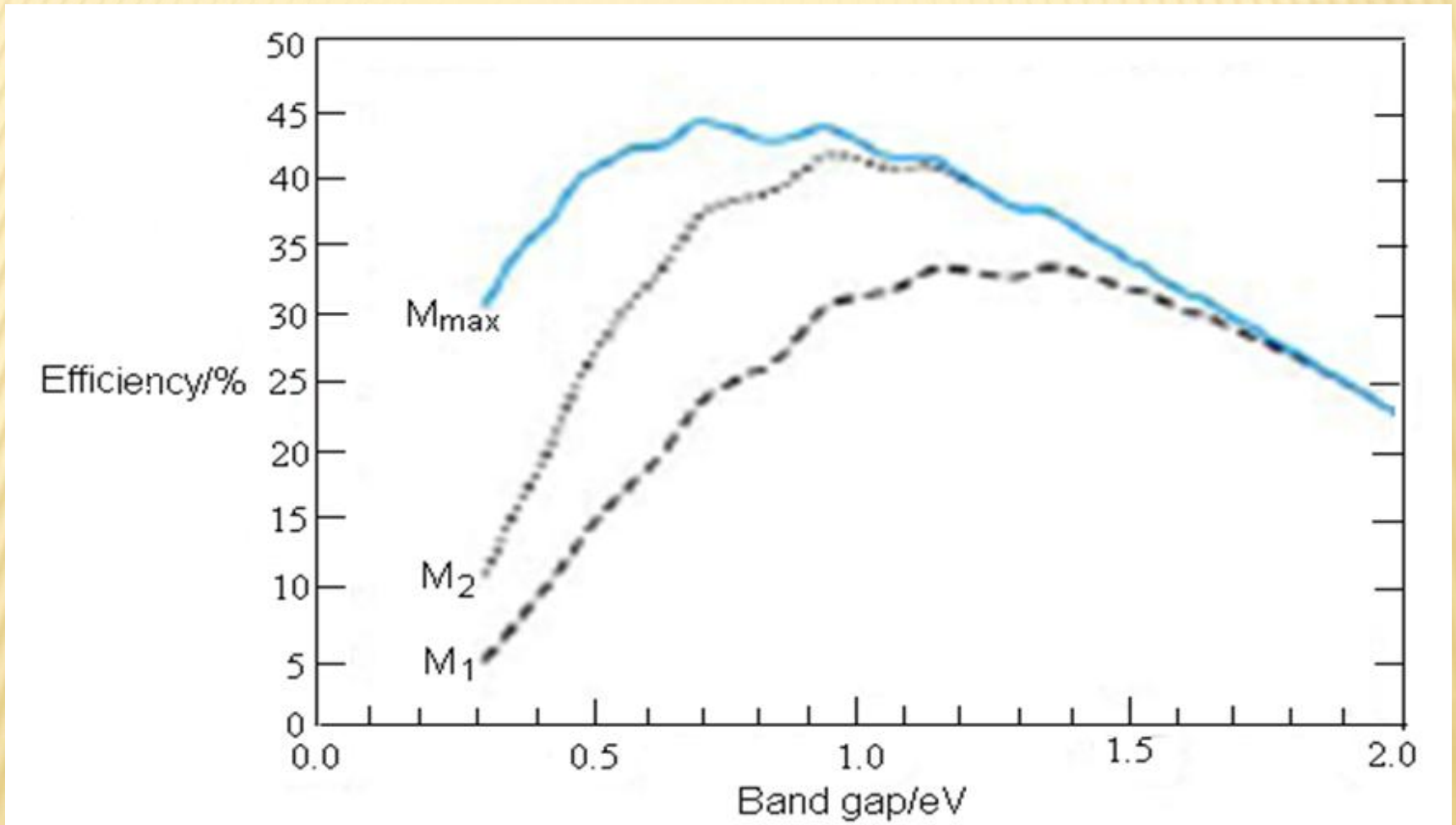
Fig 7: The efficiency versus quantum dot band gap for M_1, M_2 and M_{max} absorbers [Hanna M.C. & Nozik A. (2006)]

RESULTS AND DISCUSSION

❖ Curve M1 corresponds to absorbers without carrier multiplication. The maximum efficiency is 33.7% at E_g ~ 1.2eV in agreement with bulk semiconductor materials.

❖ Curve M2 corresponds to absorbers with carrier multiplication of 2 and has a maximum efficiency of 42% at E_g ~ 1.0eV .

❖ Curve Mmax corresponds to absorbers with the maximum number of carrier multiplication (Mmax = 7) and has a maximum efficiency of 44.4% at E_g ~ 0.7eV

CONCLUSION AND RECOMMENDATIONS

conclusion

❖ In this presentation, it has been demonstrated that, the conversion efficiency of a solar cell with quantum dots included, could be improved from 30% to 42% and beyond through

❖ (i) impact ionization which minimizes thermalization losses,

❖ (ii) the size-dependent band gap tunability of a quantum dot which also minimizes transmission losses.

THANK YOU