Photovoltaic converters with quantum objects under laser flux of subband photons

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Abstract. Quantum objects in the host material of photovoltaic converters can expand the spectral sensitivity to the long-wavelength spectral region. Samples with InAs quantum dots and thin layers in the host GaAs material were studied theoretically with the assumption of high-power laser subband irradiation input. Threshold factors have been established that affect the possibility of radiation heating. For noticeable increase in the temperature of the base material the necessary illumination values were estimated.

1. Introduction
One of the areas of semiconductor physics and technology is the embedding of quantum objects (QOs), i.e. quantum dots (QDs), and thin (wetting) layers into bulk material or active regions of p-n junctions. Such structures are able of both absorbing and emitting of light. They find their application in quantum optics, in photodetection, and in direct photovoltaic conversion of light energy.

Quantum-sized objects can be introduced into the active region of a semiconductor photovoltaic converter (PVC) aiming following: redistributing the light flux inside the structure (one-dimensional photonic crystals - Bragg reflectors [1, 2]) or expanding the spectral sensitivity of the device in the long-wavelength region due to absorption of subband photons [3]. In second case quantum wells of type I or II are formed in the active region of the structure [4, 5]. They produce a set of levels within the forbidden band of a semiconductor that serves as stepping stones to absorb additional low-energy photons and increase the photocurrent.

Type I quantum objects can be formed by low-dimensional InAs objects in the host GaAs material. Structures for PVCs were grown by MOCVD technique. An increase in the photocurrent 0.07 mA/cm² per single layer of quantum objects was observed in the samples under solar irradiation of ~136 mW/cm² [6].

The technology of built in InAs quantum objects in GaAs host material is actual for highly efficient multi-junction PVCs. Quantum objects in the middle subcell can increase the efficiency of such cells [7].

Multi-junction high-efficiency PVCs are widely used in solar concentrator modules. In these devices the optical power on photodetector surface of cell can exceed 50 W/cm² (concentration ratio 500 or more). Thus studies of the photovoltaic characteristics of converters with QOs at high and ultra-high irradiation are of interest from a physical and applied point of view.

In this work GaAs PVCs with InAs QOs in conditions of high-intensity subband irradiation are theoretically studied. For more accurate determination the factors affecting the photovoltaic parameters of the structure under test the power laser illumination was assumed. Selectively tuned light irradiation of quantum objects makes it possible to establish the relation between the current...
generation and the irradiation level. In such conditions it is also possible to reveal the thermodynamic effect of high-power laser radiation on the photovoltaic parameters.

2. Mechanisms of PVCs heating in high irradiation conditions

A large number of nonequilibrium charge carriers are generated in the PVCs if regime of ultrahigh irradiation with high-energy photons takes place. If photon energy exceeds the band gap, the existing energy difference is transferred to the crystal lattice in the process of charge carriers thermalization with a time constant of $\sim 10^{-12}$ s [8]. This is the main source of heating the semiconductor material.

There are several ways for nonequilibrium charge carriers at the bottom of the conduction band and top of the valence band to recombine: band-to-band with the emission of a photon, through the Auger recombination process, or through deep levels of defects.

The recombination mechanism through deep levels does not dominate in conditions of high charge carrier generation. The reason for this is the current saturation of defects [9]. Interband radiative and Auger recombination dominate in such condition. In case of interband radiative recombination there is no thermal energy to heat the crystal, since photons carry away a portion of power produced at radiative recombination process. In Auger processes the energy comes from nonequilibrium charge carriers recombination. It is transferred to a third carrier, which is then thermalizes to the bottom of the conduction (or top of the valence) band.

3. Subband photons heating of the PVCs with QOs

At the start of subband illumination there will be absorption only in low-dimensional structures. As the heating of QO increases, the nearby material will also heat up. The band gap of the heated host material will decrease. It will lead to the absorption of low-energy radiation in the host material. Since thermalization heating in a bulk structure is more efficient, absorption in the host material together with heat generating will grow even more intensively.

It is important to note that the heating of the host material to a light-absorbing state is possible only with the corresponding heat flux generated in QO. The “critical” power of the optical subband pumping is determined by the difference between the initial temperature of the base material and the temperature at which its absorption edge match with the wavelength of the laser radiation.

Depending on the PVC production technology, quantum dots [10] or wetting layers [6] may dominate in light absorption.

3.1. Radiation heating of quantum dots

Radiation heating of quantum dots with a diameter of $2a$ can be described as the process of heating a solid with a radial heat flux [11]. Let us assume heat density $q$ is generated in area $0 \geq r > a$ per time unit. Thus for the material with heat conductivity $\chi$ outside the sphere $r > a$ overheating is

$$\Delta T(r) = \frac{qa^3}{3\chi r}$$

If there is heat flux $Q = q \frac{4}{3} \pi a^3 = 2 \times 10^{14}$ eV/s in QD of size ~10 nm there will be GaAs overheating ~ 1K.

In 0-dimensional structures and in bulk material heating occurs in a different way because the number of allowed energy levels varies significantly. Therefore the thermalization mechanism is difficult if there are many generated nonequilibrium charge carriers. Together with this it was shown that the Auger recombination mechanism is blocked in such condition. The average time of their thermalization is limited by the interband recombination time of $\sim 10^{-9}$ s [12].

If there is only thermalization mechanism, heating generation is possible when nonequilibrium charge carriers from the second energy level of the quantum dots relax to the first (~ 0.1 eV). At the lifetime of nonequilibrium charge carriers of $\sim 10^{-9}$ s it is impossible to gain heat flux to overheat host material. The maximum temperature increase is $\sim 10^{-7}$ K. It is important to note that such an effect is possible only if there is no overlapping of neighboring QDs wave functions. Otherwise at a high
concentration of QDs a there will be no low dimensionality effects. The physical processes of bulk material will be observed.

3.2. Radiation heating of wetting layers
The thickness of the wetting layer is smaller than the size of the QD. Therefore temperature gradient can be modeled by the integration of point heat sources.

\[ \Delta T(r_{ij}) = \int_0^{L_x} \int_0^{L_y} \frac{Q}{3K|\mathbf{r} - \mathbf{r}_{ij}|} \, dx \, dy \]

where \( L_x, L_y \) – lateral PVC size, \( Q \) – heat flow of wetting layer, \( \mathbf{r} \) – position of a single point source \( \mathbf{r}_{ij} \) – point for determination the temperature.

Figure 1. Overheating of the GaAs host material of near the InAs wetting layer. It is assumed the size of the photomultiplier to be 1 mm\(^2\) in the calculations and the wetting layer generates thermal flow of \( 10^{-6} \) watts.

Figure 1 illustrates the overheating of the host material near the wetting layer. The area in the center of the light spot will be most heated. The wetting layer with an area of 1 mm\(^2\) should generate a heat of \( \sim 10^6 \) W to increase its temperature by 1 K. In the case of 2-dimensional material the energy spectrum of the structure is continuous. Therefore there are no difficult for the thermalization of charge carriers as in 0-dimensional case. Thus the generated nonequilibrium charge carrier will give the crystal lattice thermal energy of \(~0.1\) eV in case of thermalisation and \(~1\) eV in case of Auger recombination. So for the samples from [6], the radiation power density should be \(~ 10 \) W/cm\(^2\) to achieve the described effect.

4. Conclusion
In this paper the radiative heating of a GaAs PVCs with InAs QOs in high laser subband irradiation was considered. It was shown that any significant heating of the structure due to absorption of radiation in the QD is impossible. The necessary power for a noticeable temperature change of the host material cannot be generated in these objects. At high irradiation the rate of interband radiative recombination does not allow a sufficient amount of generated charge carriers to be "pumped" through the QD's set of energy levels. So there are too few thermalization acts to make significant heat flow. Absorption in wetting layers does not have such a limitation for hot charge carriers. The continuous spectrum of two-dimensional objects allows thermalize at normal speed. The temperature response to
High-power laser radiation was estimated for samples with predominant absorption of subband photons in the wetting layer. Continuous laser power irradiation of ~ 10 W/cm² is able to increase temperature of the host material nearby the wetting layer by ~1 K.

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