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# Lead sulfide colloidal quantum dot photovoltaic cell for energy harvesting from human body thermal radiation

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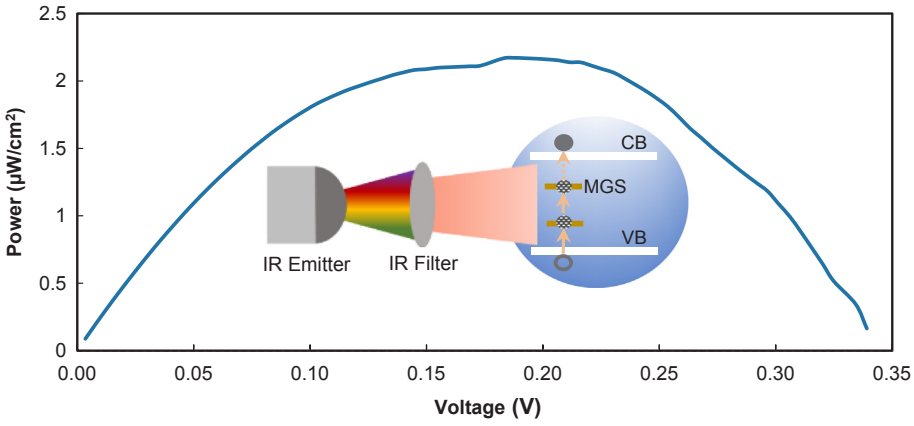
## HIGHLIGHTS

- A solution-processed photovoltaic structure based on quantum dots is developed.
- Fabricated device harvests energy from the human body thermal radiations.
- The absorption mechanism is attributed to the contribution of mid-gap states.

## GRAPHICAL ABSTRACT




## ARTICLE INFO

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## ABSTRACT

In this paper, we present the development of a solution-processed photovoltaic structure designed to convert human body thermal radiation into electricity. An active layer composed of a layer of isopropylamine-capped lead sulfide (PbS) quantum dots (QDs) covered with a layer of lithium chloride (LiCl) on top is sandwiched between a substrate and an aluminum contact. Experimental measurements reveal that the device was sensitive to infrared radiation with energies lower than the optical bandgap energy of the incorporated nanocrystals ($E_g$ = 1.26 eV), allowing one to harvest thermal radiation from a human body. We used a conceptually different approach to harvest this radiation by intentionally introducing mid-gap states to the lead sulfide quantum dots through passivation with isopropylamine and likely enabling a multi-step photon absorption mechanism.

## 1. Introduction

The reliance on energy sources based on fossil fuels motivates research on alternative sources and new energy harvesting approaches [1]. Progress in materials science provides alternative feasible solutions enabling energy harvesting from green energy sources that are sustainable and renewable. Some of the renewable energy technologies have the advantage of providing more flexibility and can be tailored to customer needs. For instance, solar cells have a wide range of potential applications from micro-scale power applications in powering portable

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electronics and sensors to large-scale power applications in supplying energy to commercial or residential needs. However, sunlight is not always an available energy source whereas thermal energy, on the other hand, is often available. A massive thermal energy is being dissipated in our world which has been neglected. For instance, the earth generates a huge amount of thermal radiation of about $10^{17}$ W and send it into the outer space [2]. The thermal radiation lies in the infrared and if it were possible to harvest it, one could consider its use in low-power consumer electronics and wearable or implanted devices used for medical or fitness applications.

The net heat dissipation of a sitting adult person is about 120 W [3]. This heat is not uniformly distributed on the surface of the body and it varies between 1 and 10 mW/cm$^2$ depending on location [4]. Although body heat could be considered to be a reliable energy source and, theoretically, it is enough to supply many daily use electronics, current technology is incapable of efficiently harvesting it. Current approaches for energy harvesting devices are primarily based on thermoelectric or pyroelectric effects. Pyroelectric generators require a time-variant temperature profile on the device to generate electricity [5]. These devices are typically not suitable for energy harvesting from the human body since the body has a very slow and limited temperature variation. Thermoelectric generators (TEGs) require a temperature gradient across the device [6]. Temperature equalization is one of the challenging problems of TEG devices. Since they need to attach to the heat source and absorb heat by conduction, the thermal conductivity of the device can decrease or eliminate the temperature gradient resulting in poor efficiency. Therefore, a mechanism is required to produce or maintain the required temperature profile in order to provide continuous energy conversion.

It has been shown that radiation is the dominant heat loss mechanism of the human body at room temperature [7]. Since the emissivity of the human skin is equal to 0.98 ± 0.01 for infrared emission between 1 and 14 μm [8], the human skin can be considered as an almost perfect blackbody radiator with an emission that peaks at around 9.5 μm. The spectral radiant power per unit area of a blackbody at wavelength λ, derived from Planck's blackbody formula, shows that the spectrum peak shifts from 9.8 μm at 23 °C to 9.35 μm at 37 °C (0.45 μm shift for 14 °C temperature variation on the skin). Therefore, body infrared radiation is an available source of energy especially for the wearable or implanted electronics.

Recently, it has been shown that exciting plasmons in nanophotonic structures enable harvesting low energy infrared photons available in room temperature [9]. Another theoretical study showed that in the thermoradiative cell, quasi-Fermi level variations in a p-n junction can convert thermal energy into electricity [10]. Rectenna [11] is another approach to harvest electromagnetic energy in a very wide spectrum including infrared light. Although these studies illustrate the ability of these methods to harvest thermal radiation, experimental investigations have been limited due to the complexity and high-cost fabrication process. This has hindered practical applications.

In this paper, we introduce a solution-processed photovoltaic structure operating based on a conceptually different phenomenon to harvest thermal radiation. Photovoltaic devices normally work based on the absorption of the photons carrying energy higher than the bandgap of the semiconductor [12]. Therefore, there is an inherent limitation associated with the band gap of the semiconductor materials for harvesting thermal radiations. The band gap of semiconductors is not narrow enough to harvest low energy infrared photons emitting from the objects at around room temperature. In the proposed structure, we intentionally generate some density of states inside the band gap of the semiconductor, called mid-gap states, to address the problem associated with the bandgap of the semiconductor. These states enable gradually promotion of the electron from the valence band to the conduction band through a multiple-step photon absorption process. This structure also benefits from a simple and low-cost fabrication process and this can address problems associated with complex and high-cost fabrication processes.

The proposed photovoltaic structure employs isopropylamine (IPAM)-capped lead sulfide (PbS) colloidal quantum dots. Colloidal quantum dots (CQDs) are solution-processed nanoscale semiconductor crystals capped with organic or inorganic materials to ensure solubility and stability. The large surface-to-volume ratio of quantum dots [13] enables one to manipulate the band structure and density of states through modifying surface properties [14]. Initial long-chain oleic acid ligands covering the surface of the PbS QDs can be replaced by short-chain isopropylamine ligands to improve charge dissociation efficiency [15] and provide suitable mid-gap states. It has been shown that organic ligands leave a high density of trap states on the surface of the PbS QDs [16], resulting in the generation of mid-gap bands (MGB) and mid-gap states (MGS) [17]. Moreover, quantum dots have the advantage of accessing spectral tunability via tailoring the size [18], shape [19], and stoichiometry [20] during the growth process. This provides an efficient solution-processed fabrication method for optoelectronic devices such as photodetectors [21], photovoltaics [22], and light emitting diodes [23].

## 2. Device structure

Schematic structures of the devices that we have fabricated are shown in Fig. 1(a) and (b). The active layer of the device, which is a thin film of isopropylamine-capped PbS quantum dots covered with a layer of lithium chloride (LiCl) on top, is sandwiched between the substrate and aluminum thin film contacts. A cross-sectional SEM image with labels is shown in Fig. 1(c). It reveals an approximately 465-nm-thick layer of PbS QDs with around 10-nm-thick layer of LiCl on top.

During the solid-state ligand exchange process, oleic acid was replaced by isopropylamine (IPAM). Fig. 2(a) shows Fourier transform infrared spectroscopy (FTIR) spectra of oleic acid and isopropylamine surface passivated PbS quantum dots. To probe the existence of isopropylamine on the surface of the PbS nanoparticles after the ligand

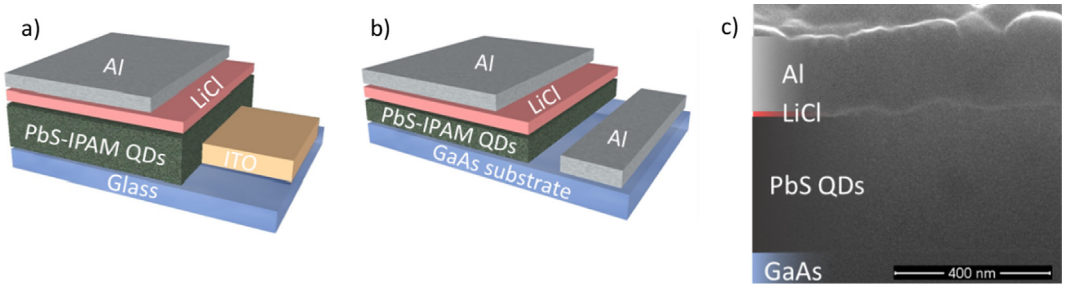


**Fig. 1.** Architecture of the fabricated device: (a) a schematic of the device with soda-lime glass as the substrate and ITO as the bottom contact; (b) a schematic of the device on a doped GaAs substrate to eliminate the effect of ambient light and infrared photons with energies higher than the bandgap energy of the PbS QDs; and (c) cross-sectional SEM image of a 10-nm-thick LiCl layer and a 465-nm-thick PbS CQDs on a GaAs substrate. The active layer, which is a thin film of isopropylamine-capped PbS quantum dots covered with a layer of LiCl on top, is sandwiched between Al contact and substrate.