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# Near-field enhanced negative luminescent refrigeration

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## Abstract

We consider a near-field enhanced negative luminescent refrigeration system made of a polar material supporting surface phonon-polariton resonances and a narrow-bandgap semiconductor under a reverse bias. We show that in the near-field regime, such a device yields significant cooling power density and a high efficiency close to the Carnot limit. In addition, the performance of our system still persists even in the presence of strong non-idealities such as Auger recombination and sub-bandgap thermal radiation from free carriers.

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## I. INTRODUCTION

When a semiconductor  $p$ - $n$  junction is under external bias, the expectation value of photon energy per mode above bandgap satisfies the Bose-Einstein distribution [1]

$$\Theta(\omega, T, V) = \frac{\hbar\omega}{e^{\frac{\hbar\omega - qV}{k_B T}} - 1} \quad (1)$$

where  $\hbar$  is the reduced Planck's constant,  $\omega$  is the angular frequency,  $q$  is the magnitude of electron's charge,  $V$  is the external bias,  $k_B$  is the Boltzmann constant and  $T$  is the temperature of the semiconductor. Thus, in the presence of a negative bias (i.e.  $V < 0$ ), the semiconductor  $p$ - $n$  junction emits less photons as compared to the same system at thermal equilibrium with  $V = 0$ . In such a situation, as far as thermal radiation properties are concerned, one can equivalently describe the semiconductor as having an apparent temperature lower than its real temperature [2–8]. This effect, i.e. the suppression of thermal radiation from a semiconductor  $p$ - $n$  junction by applying a negative bias, is commonly referred to as “negative luminescence”, and has applications such as cold shields for IR detectors [9], radiometric reference sources [10] and dynamic infrared scene projectors [10].

One potential application of negative luminescence is in the area of solid-state cooling [11, 12]. In Ref. [11], Berdahl considered two semiconductor objects having different temperatures undergoing radiative thermal exchange between them, and showed theoretically that a net heat flow from the cold to the hot object is possible when the hot object is under a negative bias. His calculation was mostly carried out in the far-field regime, in which the separation between the two bodies are much greater than all wavelengths relevant to electromagnetic heat transfer between the bodies. In such a case, the achievable power density for cooling is fundamentally limited by the Stefan-Boltzmann's law. He also noted the potential enhancement in the near field due to the high-index of the semiconductors.

In recent years there have been significant theoretical [13–22] and experimental [23–27] efforts in exploring near-field heat transfer, through which the power density can far exceed the far-field limit. Motivated by these efforts, in this paper we examine the concept of negative luminescent refrigeration in the near-field regime. We consider a configuration as shown in Fig. 1, where a narrow-bandgap semiconductor  $p$ - $n$  junction under negative bias is placed in close proximity to a dielectric material supporting phonon-polariton resonances, and show that operation in the near-field regime results in significant enhancement of both

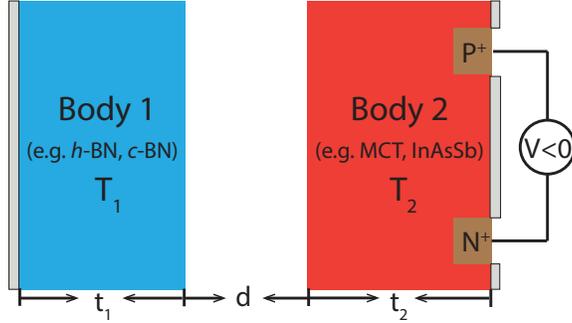


FIG. 1. Schematic of the configuration. The system consists of body 1 (material supporting surface phonon-polaritons, such as hexagonal BN (*h*-BN) and cubic BN (*c*-BN)) and body 2 (a narrow-bandgap semiconductor such as HgCdTe (MCT) and InAsSb) in close proximity. The two bodies are backed by perfect electric conductor mirrors. Body 2 is under a negative bias  $V$ .

the power density and coefficient of performance for negative luminescent refrigeration. Our work differs from in Ref. [11] two essential aspects. First of all, in our system the near field heat transfer is enhanced through the use of surface phonon-polaritons, which give rise to a much larger enhancement not limited by the indices of the semiconductors. Secondly, we also provide a quantitative evaluation of the impacts of non-idealities in the near-field regime, which was not carried out in Ref. [11].

This work is connected to but also differs significantly from a recent publication [28]. Ref. [28] considered a related cooling scheme exploiting radiative energy exchange between a colder semiconductor *p-n* junction body under external bias and another hotter thermal body. A positive bias was applied to the colder semiconductor *p-n* junction body to extract heat from the cold to the hot body. In the scheme of Ref. [28], since the electric bias in this case is applied to the cold side, the cooling power is limited by the Auger recombination and cannot reach the radiative limit. However, as we will see in the following sections, the negative luminescent scheme eliminates this constraint since the electrical bias in this case is applied to the hot side and therefore Auger recombination is no longer a direct heating process on the cold side.

The rest of the paper is organized as follows: In Section II, we briefly review the concept of negative luminescent refrigeration. In Section III, we present the results of a system consisting of Mercury Cadmium Telluride (MCT) and hexagonal Boron Nitride (*h*-BN). We conclude in Section IV.

## II. BRIEF REVIEW OF NEGATIVE LUMINESCENT REFRIGERATION

We start by a brief review of the concept of negative luminescent refrigeration. Following Ref. [11], we consider the configuration shown in Fig. 1, where body 1 at  $T_1$  is in thermal exchange with body 2 at temperature  $T_2$ . Body 2 is made of semiconductor with band gap energy  $E_g$ . In this configuration, the device forming body 2 can be fabricated in a process where one first fabricates a diode on a substrate. The substrate is then removed and finally a metal layer is deposited on the diode to act as the mirror. We assume that  $T_1 < T_2$ . The objective of negative luminescent refrigeration is to extract heat from body 1, in spite of the fact that it has a lower temperature, by applying a negative bias  $V < 0$  to the semiconductor body 2. We assume a device configuration as shown in Fig. 1 where the semiconductor region is intrinsic, and external bias is applied through two heavily doped regions labeled  $P^+$  and  $N^+$ , respectively. The convention for the signs is chosen such that a positive current corresponds to the flow of positive charge from  $P^+$  anode through the intrinsic region to the  $N^+$  cathode. The negative bias then generates a negative current  $I$ . The total electric power that is used to drive the two-body system is then  $IV$ .

A cooling device as such is characterized by its cooling power density and its efficiency. The cooling power density  $P$  is defined as the net electromagnetic power per unit area that flows from body 1 to 2. The efficiency of a device is characterized by the coefficient of performance (COP), defined as

$$\text{COP} = \frac{P \cdot \text{Area}}{IV} = \frac{P}{JV}, \quad (2)$$

where  $J = I/\text{Area}$  with the Area being the surface area of body 1 facing body 2. Since the net cooling power, which arises from the radiative exchange between the two bodies, scales linearly with Area defined here in Eq. 2, for convenience it is useful to define a current density as the total current divided by this area. The current density thus is defined in a normalized measure of the total current that passes through the device, and does not necessarily correspond to the actual electric current density within the device.

Similar to the treatment in Ref. [28], we now present a simple analytical calculation of the negative luminescent device that highlights the essential physics. Using Eq. 1, and assuming that the heat exchange between the two bodies is narrow-banded near the band

gap frequency  $\omega_g = E_g/\hbar$ , we can then define an apparent radiant temperature  $T_2^*$  by setting

$$\frac{\hbar\omega_g}{e^{\frac{\hbar\omega_g - qV}{k_B T_2}} - 1} = \frac{\hbar\omega_g}{e^{\frac{\hbar\omega_g}{k_B T_2^*}} - 1}, \quad (3)$$

and hence

$$T_2^* = T_2 \left( 1 - \frac{qV}{\hbar\omega_g} \right)^{-1}, \quad (4)$$

which is Eq. (5) in Ref. [11]. As far as the radiation properties are concerned, the semiconductor has an effective temperature  $T_2^*$  less than its thermodynamic temperature  $T_2$  in the presence of a negative bias  $V < 0$ .

In order to achieve solid-state cooling of body 1, we must have  $T_2^* < T_1$ , and therefore the applied voltage must satisfy  $V < V_t$ , where the threshold voltage

$$V_t = \frac{\hbar\omega_g}{q} \frac{T_1 - T_2}{T_1}. \quad (5)$$

In the case of a substantial negative bias, the emission from the semiconductor body 2 can be ignored. Within the same narrow-banded approximation as discussed above, the cooling power density can then be estimated as

$$P_{\max} = \hbar\omega_g F_{1 \rightarrow 2}, \quad (6)$$

where  $F_{1 \rightarrow 2}$  is the photon number flux from body 1 to body 2. Also,  $J = -qF_{1 \rightarrow 2}$ . Therefore, for  $V < V_t$ , the COP in Eq. 2 is simplified to be

$$\text{COP} = -\frac{\hbar\omega_g}{qV}. \quad (7)$$

According to the second law of thermodynamics, the COP should be bounded by the Carnot limit, i.e.

$$\text{COP} \leq \frac{T_1}{T_2 - T_1}. \quad (8)$$

From Eqs. 5 and 7, we see that COP reaches Carnot limit exactly when  $V = V_t$ , and falls below Carnot limit when  $V < V_t$ . The dependency of the COP on the voltage can be understood from Eq. 7. Each photon traversing the vacuum gap removes energy of  $\hbar\omega_g$  from body 1, at the cost of injected electric energy of  $qV$  into body 2. Therefore, the COP decreases as the magnitude of the applied voltage  $V$  increases.

We now illustrate the choice of materials and the operation regime for the device using the simple analytic model. In general, the photon flux from body 1 to body 2 is

$$F_{1 \rightarrow 2} = \int_{\omega_g}^{+\infty} d\omega A(\omega) \frac{1}{e^{\hbar\omega/k_B T_1} - 1}, \quad (9)$$

where  $A(\omega)$  is the spectral heat transfer coefficient and  $A(\omega) = A_0(\omega) = \frac{\omega^2}{4\pi^2 c^2}$  if the two bodies are in the far field, the body 1 is a blackbody and the absorption coefficient of body 2 is unity at frequencies above the band gap.  $A(\omega)$  could be greater than  $A_0(\omega)$  in the near-field case. In both near-field and far-field cases, suppose  $\hbar\omega_g \gg k_B T_1$ , Eq. 9 is approximated as

$$F_{1 \rightarrow 2} = \int_{\omega_g}^{+\infty} d\omega A(\omega) e^{-\hbar\omega/k_B T_1} \propto e^{-\hbar\omega_g/k_B T_1}. \quad (10)$$

Therefore in this case, the cooling power density is exponentially suppressed by the factor  $e^{-\hbar\omega_g/k_B T_1}$ . It follows that to have substantial cooling power density, we would like to choose a narrow-bandgap semiconductor with  $\hbar\omega_g$  on the order of  $k_B T_1$ . For operation around the room temperature 300 K, the use of narrow-bandgap semiconductor is therefore required.

A general thermal body will typically have its emissivity less than unity. Therefore, in applying Eq. 9 to a general thermal body in the far field regime, we always have  $A(\omega) < A_0(\omega)$ . Therefore, in the far-field regime, the cooling power density is limited by the Stefan-Boltzmann limit of blackbody radiation. On the other hand, since in the near-field the heat exchange can significantly exceed the Stefan-Boltzmann limit, the near-field regime represents an opportunity to significantly enhance the cooling power density achievable with negative luminescence.

### III. ANALYSIS OF A NEAR-FIELD NEGATIVE LUMINESCENT REFRIGERATION DEVICE

#### III.1. Material Systems & Geometry

The discussion in Section II highlights the essential physics of negative luminescent refrigeration, and points to the importance of performing such cooling in the near-field regime. Motivated by this discussion, here we present a detailed analysis of the system shown in Fig. 1. For the semiconductor (i.e. body 2 in Fig. 1), we use a narrow-bandgap semiconductor  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$  (Mercury Cadmium Telluride, or MCT). MCT is a commonly used material for infrared detector applications. With  $x = 0.2$ , it has a band gap of  $E_g = 0.169$  eV. In our calculation, we choose the semiconductor to have a temperature of  $T_2 = 300$  K. The bandgap of MCT therefore equals a few times  $k_B T_2 = 0.026$  eV. The dielectric constant of MCT as a function of frequency is taken from Ref. [29].

For the body to be cooled (i.e. Body 1 in Fig. 1), we assume a temperature  $T_1 = 290$  K, and choose to use hexagonal Boron Nitride ( $h$ -BN).  $h$ -BN is an anisotropic material with a uniaxial dielectric tensor as characterized by the ordinary and the extraordinary dielectric functions  $\epsilon_o$  and  $\epsilon_e$ , respectively. Both  $\epsilon_o$  and  $\epsilon_e$  have a resonance corresponding to an underlying phonon-polariton resonance. It is well known that the presence of surface phonon-polariton leads to significantly enhanced near-field thermal transfer [13], hence the choice of  $h$ -BN in our case since its phonon polariton frequency is well aligned with the band gap of MCT, corresponding to the wavelength of  $7.3 \mu\text{m}$ . The phonon-polariton resonant wavelengths, defined as the wavelengths where the imaginary parts of  $\epsilon_o$  and  $\epsilon_e$  maximize, are located at  $12.8 \mu\text{m}$  and  $7.3 \mu\text{m}$ , respectively. The dielectric function of  $h$ -BN as a function of frequency is obtained from the model in Ref. [30].

In the calculation, the thicknesses of body 1 and body 2, denoted as  $t_1$  and  $t_2$ , are chosen to be  $5 \mu\text{m}$  to ensure significant emission and absorption. The two bodies are separated by a vacuum gap of size  $d$ , and both bodies are backed by perfect electric conductor mirrors. We only consider the case where the  $c$ -axis of  $h$ -BN is perpendicular to the surface of body 1.

The setup here is a commonly used configuration for demonstrating near-field heat transfer through vacuum between two bodies. When two thermal bodies of different temperatures are brought in close proximity with separation below the thermal wavelength, the heat transfer between them can be enhanced beyond the Planck's law of blackbody radiation due to the contributions from the evanescent waves [31–33]. Such enhancement is particularly prominent when the interacting bodies support surface modes, such as surface plasmon-polariton or surface phonon-polariton [22, 34]. Similar to the scenario considered in our case, the heat transfer between a semiconductor and a polar material supporting surface phonon-polariton has also been discussed in the context of thermophotovoltaics [13] as well as thermal rectification [35, 36].

We also note that the choices of material for the two bodies are not limited to the materials considered here. Any combination of a material supporting surface resonant modes, such as surface phonon-polariton or surface plasmon-polariton, and a narrow-bandgap semiconductor whose bandgap is below the corresponding surface polariton frequency, can be used in the configuration for negative luminescent refrigeration. Either body can also have nano-patterning on the surface facing the vacuum gap to further enhance the transferred

power density.

### III.2. Computational Methods

To evaluate the performance of the negative luminescent refrigeration device, we use the formalism of fluctuational electrodynamics [16, 17, 28, 31, 37, 38]. In this formalism, one describes the heat transfer between objects by computing the electromagnetic flux resulting from fluctuating current sources inside each object. The cooling power density can then be obtained as [39, 40]

$$P = P_{\text{ideal}} = \int_{\omega_g}^{+\infty} [\Theta(\omega, T_1, 0) - \Theta(\omega, T_2, V)] \Phi(\omega) d\omega. \quad (11)$$

In Eq. 11,  $\Phi(\omega)$  is the sum of transmission factors at lateral wave vector  $\mathbf{k}_{\parallel}$  at frequency  $\omega$ , i.e.

$$\Phi(\omega) = \frac{1}{2\pi} \sum_{j=s,p} \left\{ \int_0^{k_0} \frac{d^2\mathbf{k}_{\parallel}}{4\pi^2} \frac{(1 - |r_j^{(1)}|^2)(1 - |r_j^{(2)}|^2)}{|1 - r_j^{(1)} r_j^{(2)} e^{2ik_{\perp}d}|^2} + \int_{k_0}^{\infty} \frac{d^2\mathbf{k}_{\parallel}}{4\pi^2} \frac{4\text{Im}(r_j^{(1)})\text{Im}(r_j^{(2)})}{|1 - r_j^{(1)} r_j^{(2)} e^{2ik_{\perp}d}|^2} \right\}, \quad (12)$$

where  $k_0 = \omega/c$  is the free space wave vector,  $\mathbf{k}_{\parallel} = (k_x, k_y)$ ,  $k_{\perp} = \sqrt{k_0^2 - |\mathbf{k}_{\parallel}|^2}$  is the wave vector perpendicular the surfaces of body 1 and 2,  $j = s, p$  accounts for the  $s$  and  $p$  polarizations,  $r_j^{(1)}$  and  $r_j^{(2)}$  are Fresnel reflection coefficients from vacuum to body 1 with PEC and from vacuum to body 2 with PEC for  $j$  polarization, respectively. For each  $\omega$ , in Eq. 12, the integrand peaks at the value of  $\mathbf{k}_{\parallel}$  that corresponds to the dispersion relation  $\omega(\mathbf{k}_{\parallel})$  of the surface phonon-polariton [35, 36]. The heat transfer in the near field is therefore strongly dominated by the contributions from surface phonon-polariton.

A semiconductor that is ideal for negative luminescent refrigeration should have entire emission arising from electron-hole recombination. An ideal semiconductor therefore should have emission only at frequencies above the band gap frequency. Moreover, the recombination should be completely radiative. In the ideal case, the current density  $J_{\text{ideal}}$  is

$$J = J_{\text{ideal}} = q \int_{\omega_g}^{+\infty} \left[ \frac{\Theta(\omega, T_2, V)}{\hbar\omega} - \frac{\Theta(\omega, T_1, 0)}{\hbar\omega} \right] \Phi(\omega) d\omega, \quad (13)$$

from which the COP can then be obtained using Eq. 2.

In the scheme as considered here, the inherent material non-idealities are the existence of significant non-radiative recombination, such as Auger recombination, as well as sub-bandgap thermal radiation. In the presence of non-radiative recombination, the total current

density now has contributions from both radiative and non-radiative recombination, i.e.

$$J = q (J_{\text{ideal}} + R). \quad (14)$$

where  $R$  is the non-radiative recombination rate per unit surface area, and then COP can be obtained by combining Eqs. 2 and 14.

The net sub-bandgap heat flow is from the hot body 2 to the cold body 1, and therefore represents a parasitic process that is detrimental for the objective of cooling here. In the presence of free carrier thermal radiation, the net sub-bandgap heat flow from body 2 to body 1 is expressed as

$$P_s = \int_0^{\omega_g} [\Theta(\omega, T_2, 0) - \Theta(\omega, T_1, 0)] \Phi(\omega, V) d\omega. \quad (15)$$

Here since the density of free carriers of the semiconductor depends on the voltage, the dielectric function of the semiconductor in the sub-band gap wavelength range thus also depends on the voltage.  $\Phi(\omega, V)$  is computed with a voltage correction included. The overall net cooling power density is

$$P = P_{\text{ideal}} - P_s, \quad (16)$$

and the COP can be obtained by combining Eqs. 2, 14 and 16.

The objectives of our calculation here are to illustrate the theoretical limit of the performance using the ideal case, and to consider the impact of the most fundamental non-idealities on the performance of the device. In the following, we first discuss the ideal case in Section III.3. We then discuss non-radiative recombination and sub-bandgap radiation in Section III.4 and III.5, respectively.

### III.3. Ideal Case

We consider the ideal case first. In the absence of non-radiative recombination and sub-bandgap free carrier thermal radiation, we use Eqs. 11 and 12 to compute the cooling power  $P$  and the current density  $J$ , respectively and then obtain the COP with Eq. 2.

The net cooling power densities  $P$  as a function of the magnitude of the bias for  $d = 10, 100, 1000$  nm are shown in Fig. 2 (a). For each  $d$ , when  $V = 0$ , the temperature difference between the bodies results in net heat flow from body 2 to body 1 and thus a negative value of

$P$ . Applying a negative voltage to body 2, i.e. having a negative  $V$ , results in the suppression of the radiation from body 2 and hence the increase of the cooling power density  $P$ . When  $V < V_t$ , the apparent temperature of body 2 becomes lower than that of body 1, and thus  $P$  becomes positive. As indicated in Fig. 2, in the ideal case considered here this threshold voltage  $V_t$  is independent of the gap size  $d$ . The value of  $V_t = -0.0065$  V, as obtained from simulation, compares reasonably well with the prediction of  $V_t = -0.0058$  V as obtained from the results of the simple analytical model described in Eq. 5. When the magnitude of  $V$  is sufficiently large, the heat flux from body 2 to 1 becomes negligible for the temperatures considered here and therefore  $P$  saturates to the heat flux from body 1 to 2. As  $d$  decreases from 1000 nm to 10 nm, the maximum cooling power density increases from 29.3 W/m<sup>2</sup> to 1007.0 W/m<sup>2</sup>. As a comparison, the maximum power density in the far-field limit for this system is 11.5 W/m<sup>2</sup>. Operating in the near-field regime therefore significantly increases the cooling power density beyond the far-field limit.

In Fig. 2 (b), we show the COP for the three gap separations. For all gap sizes, at  $V = V_t$ , the COP is zero as expected since the net cooling power density is zero. As  $V$  decreases below  $V_t$ , the COP quickly maximizes as then decreases as  $V$  further decreases. The COP is largely independent of the gap size. Except for the regime near  $V_t$ , the COP agrees very well with the analytical model results of Eq. 7, shown as the gray dashed line in Fig. 2 (b). For  $d = 10$  nm, the maximum COP is 25.3, which can be compared with the Carnot efficiency limit of 29 for this system. In this ideal case, the device can operate with very high efficiency.

The result in this section shows that in the absence of material non-idealities, the device shown in Fig. 1 can perform with a high COP close to the Carnot limit, as well as a high cooling power density far exceeding the far-field limit by operating in the near field. In what follows, we evaluate how the inherent non-idealities of the semiconductor influence the device performance.

#### III.4. Auger Recombination

The analysis in Section III.3 assumes that the the only carrier generation or recombination mechanism in the semiconductor is completely radiative. On the other hand, for narrow-band gap semiconductors such as MCT, there is significant Auger recombination which is

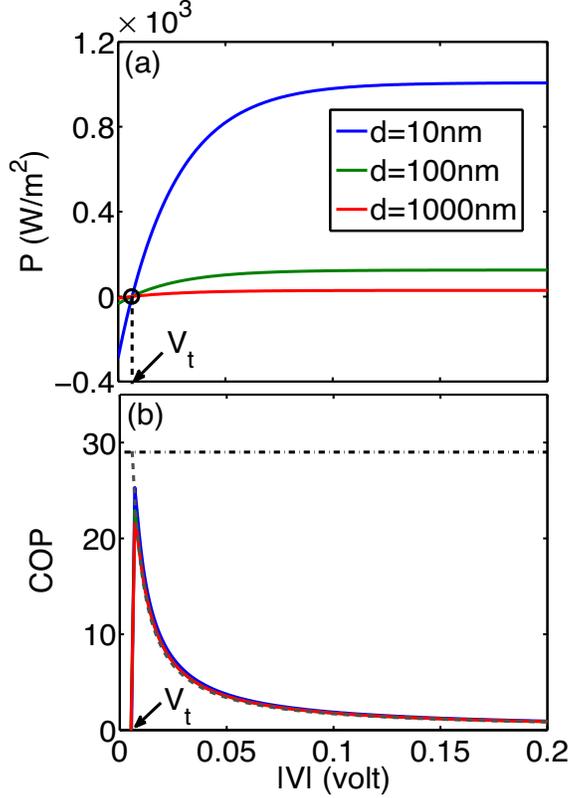


FIG. 2. (a) Net cooling power density and (b) COP as a function of the magnitude of the reverse bias. The blue, green, and red curves are for  $d = 10$  nm, 100 nm, 1000 nm, respectively. The threshold voltage  $V_t$  is labeled in both figures. In (b), the horizontal dotted line represents the Carnot efficiency and the gray dashed curve is the COP obtained using Eq. 7.

non-radiative. In this section, we evaluate the impact of Auger processes. The rate of net Auger recombination  $R$  in Eq. 14 takes the form [41, 42]

$$R = C_0 n_i^3 \left[ \exp\left(\frac{3qV}{2k_B T}\right) - 1 \right] t_2, \quad (17)$$

where  $C_0$  is the Auger recombination coefficient,  $n_i$  is the intrinsic carrier density and  $t_2$  is the thickness of the semiconductor. For MCT,  $n_i = 2.614 \times 10^{16} \text{ cm}^{-3}$  is calculated using Eq. (1) in Ref. [43] and  $C_0 = 4.88 \times 10^{-26} \text{ cm}^6 \cdot \text{s}^{-1}$  is inferred from the carrier life time data in Ref. [44]. The first and second term in the bracket of Eq. 17 arise from recombination and generation processes, respectively.

In Fig. 3 (a) we plot  $R$  as a function of the magnitude of the reverse bias. At  $V = 0$ , the semiconductor is at equilibrium and the net Auger recombination rate is zero since the generation rate balances the recombination rate as shown in Eq. 17. With a large enough

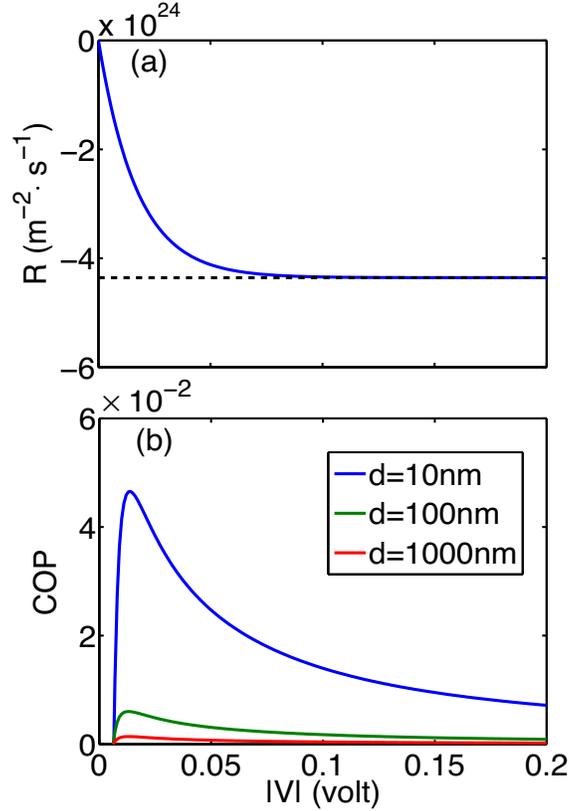


FIG. 3. (a) the net Auger recombination rate as a function of the magnitude of the reverse bias. The generation rate is plotted in the black dashed line. (b) COP as a function of the magnitude of the reverse bias in the presence of Auger recombination for  $d = 10$  nm, 100 nm, 1000 nm in blue, green and red curves, respectively.

negative bias, the net recombination rate saturates to a large negative value. In such a case, the application of large negative bias suppresses the carrier density and hence suppresses carrier recombination. As a result, there is a net generation of carriers in the system, which is represented by a net negative recombination rate.

The presence of Auger recombination does not affect the cooling power since it occurs in body 2. This can be seen from the formalism in Section III.2. On the other hand, the cooling power at large negative voltages is given by the radiation from body 1 to body 2. Therefore the cooling power is the same as Fig. 2 (a) even in the presence of Auger generation given that the temperature of body 2 is maintained constant.

Auger recombination, on the other hand, significantly degrades the COP. We compute the COP using Eqs. 2, 11 and 14. Fig. 3 (b) shows the COP as a function of the magnitude

of voltage for  $d = 10, 100, 1000$  nm in blue, green and red curves, respectively. Comparing Fig. 3 (b) with Fig. 2 (b), we see that the COP is degraded by several orders of magnitude as compared to the ideal case. In this case, the COP increases in the near field, since operating in the near field enhances radiative recombination and hence enhances internal quantum efficiency for the radiative processes in body 2.

### III.5. Sub-bandgap Thermal Radiation

For a narrow-bandgap semiconductor with high intrinsic carrier density, the free carrier can result in a large thermal emission in the sub-bandgap wavelength regime. Such sub-band gap heat transfer is detrimental since it results in a heat flow from the hot to the cold bodies. On the other hand, the free-carrier density can be suppressed using negative bias. In this section we discuss the sub-bandgap heat transfer at long wavelengths.

To model the free-carrier absorption, for simplicity, in the frequency range below the bandgap of MCT we assume a Drude dielectric function [45]

$$\epsilon(\omega) = 1 - \frac{N_e q^2 / \epsilon_0 m_e^*}{\omega^2 + i\omega\gamma_e} - \frac{N_h q^2 / \epsilon_0 m_h^*}{\omega^2 + i\omega\gamma_h}, \quad (18)$$

where  $N_e$  ( $N_h$ ) and  $m_e^*$  ( $m_h^*$ ) are the concentration and the effective mass of electrons (holes), respectively,  $\gamma_e$  ( $\gamma_h$ ) is the damping rate of the electron (hole) plasma oscillation, and  $\epsilon_0$  is the vacuum permittivity. For MCT with  $x \approx 0.2$ ,  $m_e^* = 0.0114m_0$ ,  $m_h^* = 0.55m_0$  [46], where  $m_0$  is the electron mass.  $\gamma_e$  and  $\gamma_h$  are related to the mobilities of electrons ( $\mu_e$ ) and holes ( $\mu_h$ ) through  $\gamma_e = q/m_e^*\mu_e$ ,  $\gamma_h = q/m_h^*\mu_e$ , where  $\mu_e = 1.0 \times 10^4$  cm<sup>2</sup>/(V · s),  $\mu_h = 100$  cm<sup>2</sup>/(V · s)[46]. In the presence of a bias  $V$ , the  $N_e$  and  $N_h$  scale exponentially as a function of  $V$ , expressed as  $N_e = N_h = n_i \exp\left(\frac{qV}{2k_B T}\right)$ . We also assume the mobilities are independent of  $V$ . For  $h$ BN, here we again use the dielectric function model described by Eq. (1) in Ref [30].

In evaluating the integral of Eq. 15 which is used for calculating the sub-bandgap heat transfer, instead of integrating in frequency from 0 to  $\omega_g$ , we integrate between a narrower frequency range from  $3.77 \times 10^{13}$  Hz to  $2.13 \times 10^{14}$  Hz, corresponding to the wavelengths range between  $50 \mu\text{m}$  and  $8.86 \mu\text{m}$ . This is sufficient to capture most of the contributions to sub-band gap heat exchange while reducing the computational cost. Having obtained the sub-band gap heat transfer, the cooling power is then obtained from Eq. 16. In the section

here we also take into account Auger recombination by using Eq. 14 to compute the current density. From this the COP is then computed using Eq. 2.

We shown the net cooling power density as a function of the magnitude of the reverse bias for  $d = 10, 100, 1000$  nm in Fig. 4 (a) in blue, green and red curves, respectively. In all three cases, cooling can be achieved with a negative bias having a sufficiently large magnitude. Unlike the ideal case, however, the threshold voltage in this case does depend on the spacing  $d$ . As  $d$  decreases, the sub-bandgap heat transfer increases faster than that of above-bandgap heat transfer, and therefore a larger reverse bias is needed for the device to reach the threshold condition. At  $d = 10$  nm, the net cooling power density can reach  $1006.4 \text{ W/m}^2$  at  $V = -0.2 \text{ V}$ . When the magnitude of  $V$  is sufficiently large, the free-carrier density is strongly suppressed, and the net cooling power density approaches the ideal case, as can be seen from from Fig. 4 (a).

In Fig. 4 (b), the COP as a function of the magnitude of the voltage for  $d = 10, 100, 1000$  nm is shown in blue, green and red curves, respectively. Compared to Fig. 3 (b), since the net cooling power density is degraded by the presence of sub-bandgap heat transfer, the COP is much lower for most of the values of the bias voltage. On the other hand, since the decrease of  $V$  results in the suppression of the sub-bandgap heat transfer, when the magnitude of  $V$  is sufficiently large, the COP becomes close to that in Fig. 3 (b). Therefore, for a large  $|V|$ , the COP is limited by the Auger recombination. We also note that, the voltages applied in the  $p$ - $n$  junction are in the reverse direction and serve to reduce the density of free carriers. However, for real material with defects, the carrier density is unlikely to reach an ideal limit, and thus the COP is far lower than the Carnot limit.

In addition to cooling power and COP, another metric to measure a cooling scheme is the equilibrium temperature that body 1 can reach when a negative bias is applied to the  $p$ - $n$  junction in body 2. In this system, assuming that body 1 undergoes heat exchange only with body 2, with no other parasitic heat loss mechanism, and body 2 is maintained at a temperature of 300 K with an applied voltage on body 2 of  $-0.2 \text{ V}$ , and with a 10nm gap between the bodies, the equilibrium temperature of body 1 is estimated at 226 K by a self-consistent calculation that determines the temperature through power balance. This calculation does not take into account the variation of material properties with respect to temperature. Nevertheless, the estimate does indicate that significant cooling in terms of temperature reduction can be achieved in this device.

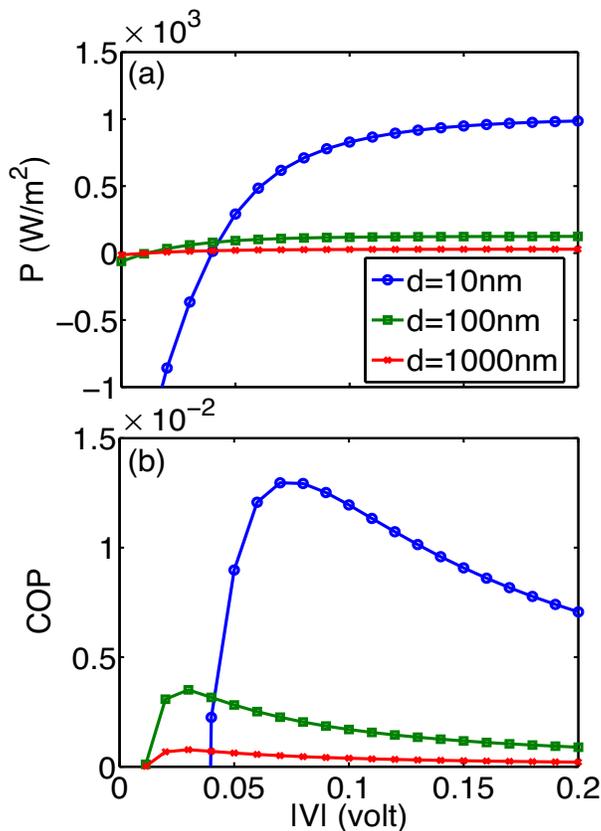


FIG. 4. (a) the net cooling power density as a function of the magnitude of the voltage in the presence of sub-bandgap heat transfer for  $d = 10, 100, 1000$  nm in blue, green and red curves, respectively. (b) the COP as a function of the magnitude of the voltage for  $d = 10, 100, 1000$  nm with both Auger recombination and sub-bandgap heat transfer included.

To briefly summarize this section, in the proposed scheme for near-field negative luminescent refrigeration as considered here, the cooling power can reach the radiative limit as defined solely by the radiative heat exchange of the two bodies, in spite of Auger recombination and sub-bandgap heat radiation from free carriers that typically occur in narrow-bandgap semiconductors. The COP in this scheme is limited by the Auger recombination, again independent from the sub-band gap heat radiation from the free carriers, since such radiation is suppressed at a negative bias with sufficiently large bias.

## IV. CONCLUSION

In this paper, we proposed a negative luminescent refrigeration device based on near-field electromagnetic heat exchange between a semiconductor under reverse bias and a polar material that supports surface phonon-polariton. The power density of this cooling effect is significantly enhanced in the near-field regime. In the ideal case, the device can operate close to the Carnot limit with a large cooling power density around  $10^3$  W/m<sup>2</sup> at a gap separation of 10 nm. We further discuss the impacts of non-idealities on the performance of the device. In the presence of strong Auger recombination, such high cooling power density persists. Even with sub-bandgap free carrier thermal radiation included, the cooling power density can still be achieved close to its maximum with a sufficiently large reverse bias. The performance and the robustness to non-idealities of this scheme is of importance to solid-state cooling applications.

Admittedly, the cooling power density and efficiency achieved by our device is lower than those of commercial thermoelectric coolers. However, due to the absence of direct contact between bodies, our device supports much faster temperature modulation than that of thermoelectric cooler. For example, when the *h*-BN is only 100 nm, the maximum cooling power density at  $T_1 = T_2 = 300$  K is 1171.3 W/m<sup>2</sup>. Given that *h*-BN has a specific heat capacity of 0.8 J/(g · K) [47] and a density of 2.18 g/cm<sup>3</sup> [47], the temperature slew rate is 6716 K/s, which is significantly faster than commercial Peltier coolers and even micro-device coolers designed for fast response times [48]. This allows the rapid modulation of temperatures which could benefit applications such as chip hot spot cooling and life science applications [48].

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- [1] C. H. Henry and R. F. Kazarinov, Quantum noise in photonics, *Rev. Mod. Phys.* **68**, 801 (1996).
  - [2] W. W. Bewley, M. J. Jurkovic, C. L. Felix, J. R. Lindle, I. Vurgaftman, J. R. Meyer, E. H. Aifer, J. E. Butler, S. P. Tobin, P. W. Norton, and M. A. Hutchins, HgCdTe photodetectors with negative luminescent efficiencies > 80%, *Appl. Phys. Lett.* **78**, 3082 (2001).

- [3] W. W. Bewley, J. R. Lindle, I. Vurgaftman, J. R. Meyer, J. L. Johnson, M. L. Thomas, and W. E. Tennant, Negative luminescence with 93% efficiency from midwave infrared HgCdTe diode arrays, *Appl. Phys. Lett.* **83**, 3254 (2003).
- [4] T. Ashley, C. Elliott, N. Gordon, R. Hall, A. Johnson, and G. Pryce, Negative luminescence from  $\text{In}_{1-x}\text{Al}_x\text{Sb}$  and  $\text{Cd}_x\text{Hg}_{1-x}\text{Te}$  diodes, *Infrared Phys. Technol.* **36**, 1037 (1995).
- [5] G. R. Nash, M. K. Ashby, J. R. Lindle, N. T. Gordon, W. W. Bewley, J. R. Meyer, J. Giess, L. Haworth, and T. Ashley, Long wavelength infrared negative luminescent devices with strong auger suppression, *J. Appl. Phys.* **94**, 7300 (2003).
- [6] T. Ashley, N. T. Gordon, G. R. Nash, C. L. Jones, C. D. Maxey, and R. A. Catchpole, Long-wavelength HgCdTe negative luminescent devices, *Appl. Phys. Lett.* **79**, 1136 (2001).
- [7] D. Hoffman, A. Hood, Y. Wei, A. Gin, F. Fuchs, and M. Razeghi, Negative luminescence of long-wavelength InAs/GaSb superlattice photodiodes, *Appl. Phys. Lett.* **87**, 201103 (2005).
- [8] A. Krier, *Mid-infrared Semiconductor Optoelectronics* (Springer, Lancaster, UK, 2006).
- [9] J. R. Lindle, W. W. Bewley, I. Vurgaftman, J. R. Meyer, J. L. Johnson, M. L. Thomas, E. C. Piquette, W. E. Tennant, E. P. Smith, and S. M. Johnson, HgCdTe negative luminescence devices for cold shielding and other applications, *J. Electron. Mater.* **35**, 1391 (2006).
- [10] T. Ashley, C. Elliott, N. Gordon, T. Phillips, and R. Hall, Applications of negative luminescence, *Infrared Phys.* **38**, 145 (1997).
- [11] P. Berdahl, Radiant refrigeration by semiconductor diodes, *J. Appl. Phys.* **58**, 1369 (1985).
- [12] P. Berdahl, V. Malyutenko, and T. Morimoto, Negative luminescence of semiconductors, *Infrared Phys.* **29**, 667 (1989).
- [13] A. Narayanaswamy and G. Chen, Surface modes for near field thermophotovoltaics, *Appl. Phys. Lett.* **82**, 3544 (2003).
- [14] C. Luo, A. Narayanaswamy, G. Chen, and J. D. Joannopoulos, Thermal radiation from photonic crystals: A direct calculation, *Phys. Rev. Lett.* **93**, 213905 (2004).
- [15] B. Guha, C. R. Otey, C. B. Poitras, S. Fan, and M. Lipson, Near-field radiative cooling of nanostructures, *Nano Lett.* **12**, 4546 (2012).
- [16] M. Krüger, T. Emig, and M. Kardar, Nonequilibrium electromagnetic fluctuations: Heat transfer and interactions, *Phys. Rev. Lett.* **106**, 210404 (2011).
- [17] C. R. Otey and S. Fan, Numerically exact calculation of electromagnetic heat transfer between a dielectric sphere and plate, *Phys. Rev. B* **84**, 245431 (2011).

- [18] R. Messina and M. Antezza, Casimir-lifshitz force out of thermal equilibrium and heat transfer between arbitrary bodies, *Europhys. Lett.* **95**, 61002 (2011).
- [19] A. Narayanaswamy and G. Chen, Thermal near-field radiative transfer between two spheres, *Phys. Rev. B* **77**, 075125 (2008).
- [20] A. W. Rodriguez, M. T. H. Reid, J. Varela, J. D. Joannopoulos, F. Capasso, and S. G. Johnson, Anomalous near-field heat transfer between a cylinder and a perforated surface, *Phys. Rev. Lett.* **110**, 014301 (2013).
- [21] C. R. Otey, L. Zhu, S. Sandhu, and S. Fan, Fluctuational electrodynamics calculations of near-field heat transfer in non-planar geometries: A brief overview, *J. Quant. Spec. Radiat. Trans.* **132**, 3 (2014).
- [22] A. I. Volokitin and B. N. J. Persson, Near-field radiative heat transfer and noncontact friction, *Rev. Mod. Phys.* **79**, 1291 (2007).
- [23] R. S. Ottens, V. Quetschke, S. Wise, A. A. Alemi, R. Lundock, G. Mueller, D. H. Reitze, D. B. Tanner, and B. F. Whiting, Near-field radiative heat transfer between macroscopic planar surfaces, *Phys. Rev. Lett.* **107**, 014301 (2011).
- [24] S. Shen, A. Narayanaswamy, and G. Chen, Surface phonon polaritons mediated energy transfer between nanoscale gaps, *Nano Lett.* **9**, 2909 (2009).
- [25] E. Rousseau, A. Siria, G. Jourdan, S. Volz, F. Comin, J. Chevrier, and J. J. Greffet, Radiative heat transfer at the nanoscale, *Nat. Photon.* **3**, 514 (2009).
- [26] A. Kittel, W. Müller-Hirsch, J. Parisi, S. Biehs, D. Reddig, and M. Holthaus, Near-field heat transfer in a scanning thermal microscope, *Phys. Rev. Lett.* **95**, 224301 (2005).
- [27] R. St-Gelais, B. Guha, L. Zhu, S. Fan, and M. Lipson, Demonstration of strong near-field radiative heat transfer between integrated nanostructures, *Nano Lett.* **14**, 6971 (2014).
- [28] K. Chen, P. Santhanam, S. Sandhu, L. Zhu, and S. Fan, Heat-flux control and solid-state cooling by regulating chemical potential of photons in near-field electromagnetic heat transfer, *Phys. Rev. B* **91**, 134301 (2015).
- [29] E. Palik, *Handbook of Optical Constants of Solids* (Academic, New York, 1985).
- [30] R. Geick, C. H. Perry, and G. Rupprecht, Normal modes in hexagonal boron nitride, *Phys. Rev.* **146**, 543 (1966).
- [31] D. Polder and M. Van Hove, Theory of radiative heat transfer between closely spaced bodies, *Phys. Rev. B* **4**, 3303 (1971).

- [32] J. B. Pendry, Radiative exchange of heat between nanostructures, *J. Phys: Condens. Matter* **11**, 6621 (1999).
- [33] J. J. Loomis and H. J. Maris, Theory of heat transfer by evanescent electromagnetic waves, *Phys. Rev. B* **50**, 18517 (1994).
- [34] O. Ilic, M. Jablan, J. D. Joannopoulos, I. Celanovic, and M. Soljačić, Overcoming the black body limit in plasmonic and graphene near-field thermophotovoltaic systems, *Opt. Express* **20**, A366 (2012).
- [35] L. P. Wang and Z. M. Zhang, Thermal rectification enabled by near-field radiative heat transfer between intrinsic silicon and a dissimilar material, *Nanoscale Microsc. Therm.* **17**, 337 (2013).
- [36] P. J. van Zwol, K. Joulain, P. Ben-Abdallah, and J. Chevrier, Phonon polaritons enhance near-field thermal transfer across the phase transition of VO<sub>2</sub>, *Phys. Rev. B* **84**, 161413 (2011).
- [37] S. M. Rytov, *Theory of Electric Fluctuations and Thermal Radiation* (Air Force Cambridge Research Center, Bedford, MA, 1959).
- [38] W. C. Chew, *Waves and Fields in Inhomogeneous Media* (IEEE, New York, 1995).
- [39] J. Dai, S. A. Dyakov, and M. Yan, Enhanced near-field radiative heat transfer between corrugated metal plates: Role of spoof surface plasmon polaritons, *Phys. Rev. B* **92**, 035419 (2015).
- [40] M. Francoeur, M. P. Menguc, and R. Vaillon, Spectral tuning of near-field radiative heat flux between two thin silicon carbide films, *J. Phys. D: Appl. Phys.* **43**, 075501 (2010).
- [41] T. Tiedje, E. Yablonovitch, G. Cody, and B. Brooks, Limiting efficiency of silicon solar cells, *Electron Devices, IEEE Transactions on* **31**, 711 (1984).
- [42] S. Sandhu, Z. Yu, and S. Fan, Detailed balance analysis of nanophotonic solar cells, *Opt. Express* **21**, 1209 (2013).
- [43] J. L. Schmit, Intrinsic carrier concentration of Hg<sub>1-x</sub>Cd<sub>x</sub>Te as a function of  $x$  and  $T$  using  $\mathbf{k} - \mathbf{p}$  calculations, *J. Appl. Phys.* **41**, 2876 (1970).
- [44] P. E. Petersen, Auger recombination in Hg<sub>1-x</sub>Cd<sub>x</sub>Te, *J. Appl. Phys.* **41**, 3465 (1970).
- [45] C. Fu and Z. Zhang, Nanoscale radiation heat transfer for silicon at different doping levels, *Int. J. Heat Mass Transfer* **49**, 1703 (2006).
- [46] A. M. Itsuno, *Bandgap-engineered HgCdTe infrared detector structures for reduced cooling requirements* (Ph.D dissertation, University of Michigan, 2012).

- [47] I. P.-T. Institute, “NSM archive - physical properties of semiconductors,” (1998).
- [48] H. Bottner, in *Proc. 24th ICT* (2005) pp. 1–8.