High-temperature Si linear light down converter with 220% efficiency

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The authors report the fundamentals and technology of the linear light down-conversion process, which is based on the possibility of enhancing thermal emission of semiconductors in the spectral range of intraband electron transitions (midinfrared and long-wave infrared) by the shorter wavelength interband excitation. They realized conditions (the 1.15-μm signal-in wavelength and 2- to 20-μm signal-out wavelengths, $T \sim 500$ K) when a Si device demonstrated the 220% power conversion efficiency. They discuss the concept for incoherent broadband light down-converters made of indirect bandgap semiconductors and fueled with thermal energy (controlling light with heat process).

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Linear light down-conversion (LDC) has been a convenient method for generating light by applying a short wavelength photon to a medium that responds by emitting one, two, or more longer wavelength photons. Such LDC processes like photoluminescence in semiconductors and quantum cutting in phosphors have gained significant interest due to promising practical applications. The LDC by photoluminescence is a way of creating high-temperature 3 to 5 μm-light emitting devices (LEDs).[1] Blue LEDs coupled with a phosphor down-conversion layer offer a solid-state solution for white lighting.[2] The quantum cutting in rare-earth-doped materials, finds applications in the fabrication of mercury-free fluorescent tubes, and plasma display panels.[3] Proposals to convert high-energy photons toward lower energies for which the solar cell works more efficiently are also worth mentioning.[4] The disadvantage, however, is that the power conversion efficiency of LDC mentioned is lower than 100% because the process comes at the cost of an incident photon. Due to activation of nonradiative decay processes (such as the multiphonon emission or free carrier Auger recombination), LDC efficiency degrades when the temperature or converted wavelength increase.

In this paper, we examine the application of the transparency modulation technique to the linear LDC process aimed to achieve the power conversion efficiency (the signal-out power per signal-in power relation) of greater than 100%. This approach is based on the possibility of enhancing the thermal emission (TE) power of semiconductors in the spectral range of intraband electron transitions [midinfrared and long-wave infrared (IR), free carrier absorption band] by the shorter wavelength optical signal (visible to near-IR, fundamental absorption band). By demonstrating the use of silicon for this purpose, we come up with the concept for an efficient temperature-activated incoherent linear light down-converter made of indirect bandgap semiconductor (controlling light with heat process).

The details of our approach appear as follows. The TE spectral power P_λ of a body with the thickness d, reflection coefficient R and absorption coefficient k, which is kept at constant temperature T

$$P_\lambda = \varepsilon_\lambda J_\lambda(T) \tag{1}$$

is a product of two factors. Specifically, $J_\lambda(T)$, that is, Planck's spectrum of black-body radiation and the body emissivity ε_λ (which equals the absorptivity) that can be expressed as

$$\varepsilon_\lambda = (1-R)(1-\eta)(1-R\eta)^{-1}, \tag{2}$$

where

$$\eta = \exp\left(-\int_0^d k(x)dx\right) \tag{3}$$

is the optical transparency of a body and the wavelength (λ) dependence of R and k is omitted for brevity. By definition, a black-body emissivity is unity and its TE spectrum is a well-known Planck's distribution (Fig. 1, curve 3). Real body specificity is in the emissivity spectrum as the reflection and absorption coefficients are wavelength dependent values. Therefore, the TE spectrum fingerprints reflect the nature of energy transitions in a body both in the equilibrium and (what is most important in our case) upon different excitation processes.[5]

In semiconductors, there are two wavelength bands with different emissivity shown in Fig. 1. In the fundamental absorption band ($\lambda_1 < hc/E_g$, h: Planck's constant, c: the velocity of light, E_g: a semiconductor bandgap, band I), bulk materials are opaque due to high interband absorption

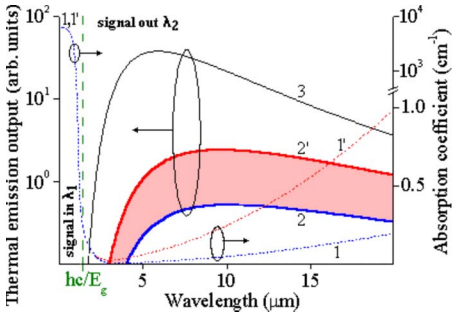

FIG. 1. (Color online) The spectral position of bands I and II is shown schematically in respect to the Si bandgap. The $k_2(\lambda)$ and $P_2(\lambda)$ dependencies in the signal-in off (1, 2) and signal-in on (1′,2′) states, respectively. Shaded region: ΔP value induced by a signal-in. 3: Planck's distribution of the black-body radiation at $T = 500$ K.

coefficient k_1. On the contrary, beyond the fundamental absorption ($\lambda_2 > hc/E_g$, band II), undoped semiconductors are highly transparent. The absorption coefficient in this band $k_2 = k_n + k_p + k_{ph}$ is connected to the lattice absorption k_{ph} and electron (n) and hole (p) absorption, $k_n + k_p = \sigma_n n + \sigma_p p$, where σ_n, σ_p are free carrier absorption cross sections of IR photons. What follows from this is the possibility to enhance the TE in the band II through the photoexcitation of free carriers with higher energy photons from the band I. This light down conversion technique, also referred to as the transparency modulation technique,[6] is easy to perform if the temperature of a semiconductor is higher than that of the background. Recently, we have shown that this approach makes it possible to use indirect bandgap semiconductors (such as Ge or Si) as IR emitters and IR dynamic scene simulation devices[7,8] and for testing recombination parameters in silicon.[9] In what follows below, we will be interested in the power conversion efficiency of this down conversion optical process.

When exposed to a light (signal-in) with the power of $P_1 = I_1 hc/\lambda_1$, an additional concentration of electrons and holes in a wafer takes the form $\Delta n = \Delta p = (1 - R_1)\, I_1 \tau_{\text{rec}}/L_d$, where I_1 is the density of incident photons per second, τ_{rec}, L_d are the effective carrier lifetime and diffusion length, respectively, and the inequality $k_1 L_d > 1$is valid.

These nonequilibrium free carriers affect both k_2 and P_2 values (see curves 1, 2 and 1′, 2′ in Fig. 1). With P_{02} and η_{02} to denote the initial values P_2 and η_2, the modulated TE power (signal-out) bidirectionally escaping the wafer in the band II $[\Delta P_\lambda = P_2(\lambda) - P_{02}(\lambda)]$ can be calculated by the expression[5]

$$\Delta P_\lambda = \frac{[1 - R_2]^2 [\eta_{0_2}(\lambda) - \eta_2(\lambda)]}{[1 - R_2 \eta_2(\lambda)][1 - R_2 \eta_{0_2}(\lambda)]} [J_\lambda(T) - J_\lambda(T_b)], \quad (4)$$

where T_b is the temperature of background. According to Eq. (4), R_2, τ_{rec}, and k_2 need to be known in order to calculate the power conversion efficiency that is the integrated in the band II ΔP_λ value (see shaded region on Fig. 1) divided by the signal-in power P_1. $R_1 \approx R_2 = 30\%$ was determined from the known refractive index of Si. It was assumed that the material is intrinsic at the temperatures of test. To estimate $k_{02}(\lambda)$ and $\eta_{02}(\lambda)$, we neglected the lattice absorption and used intrinsic carrier concentration versus temperature dependence $n_i = 3.88 \times 10^{16}\, T^{3/2} \exp(-7000/T)\ \text{cm}^{-3}$ (Ref. 10). For the temperature and wavelength dependence of the $(\sigma_n + \sigma_p) = k_{02}/n_i$, we used the equation $k_{02} = 4.15 \times 10^{-5}\, \lambda^{1.51}\, T^{2.95} \exp(-7000/T)\ \text{cm}^{-1}$ (where λ is in μm, T is in K, and k_{02} is in cm^{-1}) that is believed to be valid for wavelengths between 1 and 9 μm and temperatures ranging from 300 to 800 °C (Ref. 11). The $\tau_{\text{rec}}(T)$ dependence was measured by analyzing the signal-out decay curve (beginning below 50% of the maximum decay signal) after excitation of free carriers with a pulsed Nd:YAG laser ($\lambda_1 = 1.06$ μm, the pulse energy is chosen to fulfill low injection requirement).

The hypothesis that power conversion efficiency of the LDC process could exceed 100% is confirmed by the results of calculations (Fig. 2) with the following distinctive features. First, this process is temperature activated. This is due to the nature of photons and phonons. The particles are bosons and their concentration increases with temperature increase. As a result, free electron/hole is easy to make an indirect transition inside the conduction/valence band by interacting with IR photon and phonon at a higher temperature. Indeed, as free carrier relaxation time (τ_{rel}), exponentially decreases when temperature increases, the number of IR photons generated by each free electron/hole (that is $\tau_{\text{rec}}/\tau_{\text{rel}}$ value) increases. Secondly, the power conversion efficiency of the process depends on the initial transparency of a material. This is natural consequence of the fact that only an optically thin semiconductor ($k_{02} d \ll 1$) allows for high-intensity contrast between $P_2(\lambda)$ and equilibrium value P_{02}. For this reason, the thermal generation of free carriers (that increases $P_{\lambda 0}$) makes the process less efficient at $T > 500$ K (see high-temperature tail in curves 3, 4). Fortunately, the problem could be avoided in part by thinning a wafer. Thirdly, the background radiation that increases P_{02} should be minimized, while reflecting from or transmitting through a wafer, this radiation affects the intensity contrast (see curves 1, 2). Finally, there is the fundamental limit for the signal-out power: P_2 cannot exceed the black-body power at temperature of device.

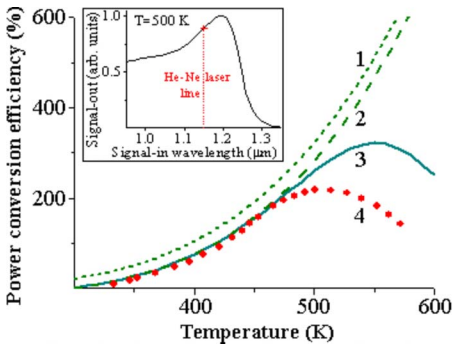

FIG. 2. (Color online) Power conversion efficiency of LDC versus temperature. 1–3: theory [$\tau_{\text{rec}} = 4$ ms. 1: $T_b = 0$, $k_{02} = 0$; 2: $T_b = 300$ K, $k_{02} = 0$; 3: $T_b = 300$ K, k_{02}: data taken from Ref. 11]. 4: Experimental results. Inset: Signal-out dependence on signal-in wavelength in respect to a He-Ne-laser line.

The samples for experiments were prepared as follows. We used a 5-mm-thick 170 Ω cm float zone n-Si wafers. Both surfaces of wafers were optically polished to prevent light scattering, and etched to minimize surface recombination velocity (s). By our tests, this value was of about 100 cm/s in the temperature range of interest while τ_{rec} increased from 2 ms (300 K) to 4 ms (500 K).

The experimental arrangement is shown in Fig. 3(a). The wafer was packaged into a beltlike molybdenum heater. By controlling the current in the heater circuit, wafer heating (that was controlled by the thermocouple and IR camera) was achieved up to 573 K. The signal-in beam λ_1 was the 1.15-μm line of a He-Ne laser (3-mW power). This beam was modulated by a mechanical chopper at the frequency of 20 Hz and focused onto a 1.5-mm-diameter area on the back facet of a wafer. The TE escaping the front facet was registered over the 2–20 μm band at the 4-cm distance with a

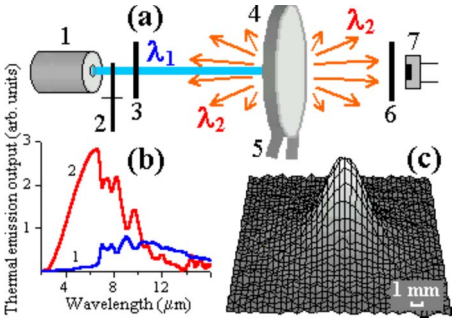

FIG. 3. (Color online) (a) Arrangement for measuring the LDC efficiency. 1: He-Ne-laser, 2: mechanical chopper, 3: H_2O filter, 4: Si wafer, 5: heater, 6: Ge filter, 7: pyrodetector. (b) Spectral distribution of P_{02} (1) and ΔP (2) at $T=500$ K. (c) The 2D signature of TE signal-out captured by the 3–5 μm thermal imaging camera from the front facet.

pyroelectric detector with a 2-mm-diameter sensitive area, which fed into a lock-in amplifier. The total front-facet hemisphere output was calculated by taking into account its Lambertian angular dependence, which we confirmed with independent measurements. Special care was taken to ensure that the IR signals were, in fact, due to the TE induced by free carriers. The 1-mm-thick water filter placed between a laser and a wafer prevented the IR radiation emitted by heated laser parts from passing through a wafer. The 0.8-mm-thick Ge filter (cut on $\lambda \approx 2$ μm) placed in front of a detector absorbed both the laser beam, which could pass through a wafer and the interband photoluminescence signal. Positioning a monochromator between Ge filter and the detector allowed measuring spectral distribution of the TE output. The two-dimensional (2D) signature of signal-out was recorded with a thermal imaging camera operating in the 3–5 μm band. In addition, $(\Delta P - I_1)$ dependence had slope of unity, indicating that ΔP varied linearly with a signal-in power, up to the highest level used ($\Delta P \sim k_2 d$, high-transparency mode).

Shown in Fig. 3(c) is the 3–5 μm camera image (signal-out) generated by a low-power laser beam at the back facet and recorded at the front facet at $T=500$ K [$k_1=17$ cm^{-1} (Ref. 12)]. As the TE magnitude is proportional to the local excess carrier concentration, the radial degradation of signal-out is due to free carrier recombination and diffusion processes. Therefore, decay length is directly related to the effective diffusion length L_d and is long as 1.5 mm in our test. Note, $L_d=(D\tau_{rec})^{0.5}=1.7$ mm by taking the measured $\tau_{rec}=4$ ms and bipolar diffusion coefficient $D=7$ cm^2/s from data in the literature[13] that was received also by using the modulated thermal emission study.

Figure 3(b) shows the signal-out spectrum recorded at $T=500$ K. Also shown is the $P_{02}(\lambda)$ dependence with fingerprints which are due to oxygen impurity and lattice multiphonon absorption.[14] As can be seen, the modulated TE signal is similar to Plank's radiation spectrum. However, emission peaks at the $P_{02}(\lambda)$ dependence transform naturally into dips in the ΔP_λ spectrum. Meanwhile, to a fairly good approximation, the device can be referred to as a broad-band gray emitter.

Figure 2 (curve 4) shows the two-facet power conversion efficiency as a function of temperature for a wafer tested at $T_b=300$ K. The over 100% values occur in the temperature range $425<T<575$ K while the peak value is of 220%. We also observed a decrease in conversion efficiency at $T>500$ K, which can be explained by gradual wafer opaqueness, induced by thermal generation of free carriers (experimental data is somewhat lower than the theoretical curve due to the parasitic lattice absorption neglected in the theory). Although we have not tried removing the room-temperature background, we believe that such an experiment would result in higher efficiency than the experiment currently being discussed. Efforts to increase the device efficiency by thinning the wafer for operating at higher temperature were limited by a comparably high s value that should have affected τ_{rec} in thin wafers. The estimates show that if τ_{rec} were of about 10 ms in 0.1-mm-thick Si wafer that remains initially transparent at high temperature, the power conversion efficiency could have exceeded 1000% at $T \geqslant 700$ K. Note that these Si parameters are not exotic—s of 0.25–4.0 cm/s and τ_{rec} of 35 ms and even exceeding 100 ms in FZ material are well documented in literature.[15]

Summarizing, we presented the concept for temperature-activated incoherent broad-band light down converter made of indirect bandgap semiconductors and capable of light "amplification" through controlling light with a heat process. Even if the parameters of the Si wafer and signal-in wavelength were not optimized, we experimentally demonstrated power conversion efficiency of 220% at $T=500$ K and >100% values for a very large temperature range. Contrary to a conventional semiconductor optical amplifier based on the stimulated interband carrier radiative recombination in a narrow above bandgap amplification window ($\lambda_2 \approx \lambda_1$), the device is based on the intraband spontaneous emission (carrier-IR photon-phonon interaction) in a wide below bandgap window ($\lambda_2 \gg \lambda_1$). The challenge to practical implementation of the strategy described consists of material bandgap engineering in the electronic domain [higher $\tau_{rec}(\sigma_n+\sigma_p)$ product, stronger $k_2=f(\lambda_2)$ dependence] and photonic engineering (transparency coating, optimum λ_1 and d values) in the optical domain.

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