This is an electronic reprint of the original article.
This reprint may differ from the original in pagination and typographic detail.

Casado, Alberto; Radevici, Ivan; Sadi, Toufik; Oksanen, Jani

On the temperature dependence of the efficiency of electroluminescence

Published in:
Journal of Applied Physics

DOI:
[10.1063/1.5124566](https://doi.org/10.1063/1.5124566)

Published: 07/11/2019

Document Version
Peer reviewed version

Please cite the original version:
Casado, A., Radevici, I., Sadi, T., & Oksanen, J. (2019). On the temperature dependence of the efficiency of electroluminescence. *Journal of Applied Physics*, 126(17), [173102]. <https://doi.org/10.1063/1.5124566>

On the temperature dependence of the efficiency of electroluminescence

Alberto Casado,^{1, a)} Ivan Radevici,¹ Toufik Sadi,¹ and Jani Oksanen^{1, b)}*Engineered Nanosystems Group, School of Science, Aalto University, P.O. Box 12200, FI-00076 AALTO, Finland*

(Dated: 15 October 2019)

Electroluminescent cooling (ELC) of light-emitting diodes (LEDs) generally requires very high light emission efficiency. Earlier studies of electro- and photoluminescence suggest that temperature strongly affects the light emission efficiency and therefore it is useful to explore the temperature range below room temperature (RT) where ELC might be easier to observe. With that purpose in mind, we electrically characterised four differently sized (0.2, 0.5 and 1 mm diameter) test devices, consisting of LEDs coupled with integrated photodetectors (PDs), at temperatures ranging from 100 K to 300 K to investigate how the temperature affects the efficiency of the structures in practice. We found that, for the studied devices, both the quantum efficiency (QE) and the overall efficiency indeed increase for low temperatures and reach peak values at temperatures clearly below RT. We also found that the temperature at which the peak efficiency occurs shifts towards higher values as the absolute value of the efficiency increases.

I. INTRODUCTION

Light emitting diodes (LEDs) have revolutionised the lighting industry by providing an efficient way of converting electricity to light. However, it is less frequently recalled that, at least in theory, they can also absorb heat to emit the light, and cool down in the process^{1,2}.

Upon spontaneous emission, the injected carriers in an LED absorb energy from the lattice at a finite temperature, before they radiatively recombine and emit light. This effect can be easily understood e.g. by considering the average photon energy E emitted by an LED which, in the Boltzmann approximation for parabolic bands³, is given by $E \sim E_g + 3/2k_B T$, where E_g is the bandgap energy of the semiconductor, k_B is the Boltzmann constant and T is the absolute temperature at which the LED operates. The previous expression states that the average energy of the emitted photons is larger than the bandgap of the active region. When the light emission happens at excitation energies lower than the bandgap, the additional energy is obtained from the thermal energy of the crystal. In this regard, an LED can be seen as a heat engine which collects heat from the lattice (i.e. from the surroundings) and converts it into photons carrying an energy higher than the input electrical energy.

The possibility of electroluminescent cooling (ELC) of an LED is based on the emission of photons with total energy larger than the injected electrical energy, resulting from biasing the LED at voltages below the active material band-gap energy. The total energy of the generated photons that way is greater than the injected electrical energy and the energy difference is provided by the crystal lattice heat in the LED⁴. Although the fundamental aspects of ELC are relatively well understood⁵⁻⁸, and experimentally reported at very low powers⁹ or locally in thermophotonic emitter-absorber configuration¹⁰, it has not been observed at conditions allowing practical applications, due to different technological challenges in the devices fabrication and structure¹¹.

The efficiency of an LED as a heat-pump should depend on temperature, considering that the thermal energy (i.e. the amount of heat available for compensating the difference between injected electrical energy and the active material bandgap) also depends on temperature. In contrast, the quantum efficiency of an LED generally increases when the ambient temperature decreases due to several effects related with factors such as non-radiative recombination or surface recombination¹²⁻¹⁵. This contrast between expected fundamental trends makes it hard to predict what is the optimal temperature range for the first demonstrations of high-power ELC. While there is a number of qualitative computational studies on the effects of temperature for ELC observation^{6,16}, it has not been yet experimentally studied in this context.

In this paper, we study the temperature dependence of the light emission and detection (in the range 100 K – 300 K) and its implications on high-power ELC using an optically coupled emitter and absorber system^{11,17,18}. This configuration, where a double-heterojunction (DHJ) LED acts as the emitter of photons and a GaAs homojunction photodetector (PD) as the absorber has produced this far the highest directly measured quantum efficiencies for GaAs LEDs¹⁰, making the structure well suited for studying the fundamental properties of devices intended for ELC, partly due to photon collection within the structure leading to alleviating some of the common light-extraction difficulties. Furthermore, the PD serves to directly probe the LED performance, as well as to estimate the lower limit for the photon-energy transport efficiency. Due to a high thermal conductivity, this structure does not allow to observe a significant temperature difference between the LED (heat source) and the PD (heat sink) since they are not thermally isolated from each other.

We find that our LEDs are most efficient at the temperature of around 250 K and close to locally cooling down, despite the unoptimised material properties. Additionally, we show that after reducing the surface recombination velocity, an imagined optimised device would locally cool down.

^{a)}Electronic mail: albertoo.casado@aalto.fi^{b)}Electronic mail: jani.oksanen@aalto.fi

II. EXPERIMENTAL DETAILS

A. DDS structure

The structures studied in this work consist of a double-heterojunction (DHJ) GaAs/AlGaAs LED structure grown on top of a GaAs p-n-homojunction PD¹⁷, branded as the double diode structure (DDS). The basic device structure is shown in Fig. 1. The epitaxial structures were fabricated by metalorganic vapour phase epitaxy (MOVPE), and the properties of each layer are shown in Table I. Each epistructure was processed to contain a selection of circular mesas of different diameters and contact regions. The contacts were formed by AuZn/Au and Ni/AuGe layers deposited on top of the p- and n-GaAs regions, respectively. The fabrication and processing details can be found in ref.¹⁷. In principle, the light emitted by the DHJ LED is guided towards the photodiode either directly or after reflection from the top contact.

FIG. 1. Top and side view of the DDS structure, and a representation of the $I - V$ curves measuring setup.

B. DDS characterisation and analysis

The DDS structures were characterised by simultaneously measuring, using a 4-point-probe setup, the currents of the LED and PD, I_1 and I_2 respectively, as a function of the bias voltage U_1 applied to the LED while short-circuiting the PD. Figure 1 shows the measurement setup schematics. Af-

TABLE I. Layer properties of the DDS devices shown in this work.

Layer	Material	Doping	Doping density (cm ⁻³)	Thickness (nm)
1	p-GaAs cap contact	p++	1.0e19	20
2	p-Al _{0.5} GaAs	p++	1.0e19	200
3	p-Al _{0.3} GaAs	p	3.0e17	500
4	i-GaAs	-	-	300
5	n-Al _{0.3} GaAs	n	1.3e17	300
6	n-Al _{0.5} GaAs	n++	1.3e17	800
7	n-AlAs etch stop	n++	1.0e18	15
8	n-GaAs contact	n+	5.6e18	20
9	n-GaAs		1.0e18	700
10	p-GaAs		3.0e17	3000
11	p-AlAs etch stop	p++	3.0e18	15
12	p-GaAs contact	p++	1.0e19	50
13	p-GaAs buffer		5.0e18	100
14	p-GaAs substrate		1.0e18	

ter systematic characterisation of approximately 100 devices at room temperature, four of the best (highest efficiency) devices were chosen and prepared for low T measurements. The chosen devices consisted of one 0.2-mm-diameter, two 0.5-mm-diameter and one 1-mm-diameter device. The varying size allows additional insight on how the devices' perimeter-to-area ratio affects the recombination and performance. The devices were first attached to a sample holder, using silver paste to allow maximum thermal conductivity, and afterwards the DDS contacts were wire-bonded to metallic pads on the said sample holder, which was placed inside a cryostat at a pressure $P \sim 5 \times 10^{-5}$ mbar. The temperature was varied within the range 100 K – 300 K. The cold finger had a built-in calibrated temperature sensor. In addition to the information obtained from the sensor and to verify that the devices were operating at the nominal temperature, an estimate for the operating temperature was extracted from the $I - V$ curves as $T = (q/nk_B) \times (dU/d[\ln(I_1)])$, at the bias where $dU/d[\ln(I_1)]$ was minimum. Assuming an ideality factor $n = 2$ in the previous expression, the difference between the nominal temperature (as measured by the built-in sensor in the cold finger of the cryostat) and the estimated temperature was lower than 10% for temperatures above 125 K, while it started to gradually increase for lower temperatures. This could be a first indication of carrier freeze-out and/or a change of the ideality factor with temperature. For this reason, the results shown here are limited to temperatures higher than 100 K, since the behaviour at lower temperatures would need further analysis of physical simulations and new measurements.

C. Numerical modelling

The experimental work presented in this paper is accompanied by extensive physical simulations, used to analyse and interpret the experimental data. As described in Ref.¹⁹, we use a charge carrier transport model solving for the drift-diffusion equations, to determine the distribution of the electrostatic potential and the quasi-Fermi levels for electrons

On the temperature dependence of the efficiency of electroluminescence

and holes, and extract the corresponding simulated current-voltage characteristics and relevant figures of merit. The combination rate R is modelled using the well-known parameterized formula for radiative, Shockley–Read–Hall (SRH) Auger recombination, and surface and interface non-radiative recombination²⁰. In our calculations, we use the temperature dependence relationships given in Ref.⁶ for the bulk recombination parameters, including the SRH (A), radiative (B) Auger (C) constants. The temperature dependence of the surface recombination velocities at the LED mesa walls are determined by fitting to experimental data. The dependence of the electron and hole mobilities on temperature is implemented using the model described in Ref.²¹. The standard formulation for the band gap temperature dependence is $E_g(T) = E_g(T = 0) - \alpha T^2 / (T + \beta)$ (see e.g. Ref.²²). For materials forming the studied structures, we use the dependencies reported in Ref.²³, for the band gap and other relevant parameters, such as the effective densities of states.

The DDS devices incorporate three terminals, all described by Dirichlet-form boundary conditions. The LED itself is used in the customary manner, while the PD is short-circuited. For the present purposes, optical coupling between the LED and PD is included using the following simple model. The electron-hole recombination term R_{LED} in the LED active region is coupled to an electron-hole generation term G_{PI} in the photodiode layers through the optical coupling constant χ via the relation $G_{PD} = \chi R_{LED}$. The coupling constant is evaluated by estimating the reflection coefficient of a multilayer system including the top (p-type) LED metal contact and the non-transparent top ‘cap’ GaAs layer, as described in Ref.¹⁹. It is estimated to be no less than 90%, when using the refractive indices reported from Ref.¹⁷ and literature. The attenuation of light in the GaAs layers forming the PD is approximated using the Beer-Lambert law. Further details of the model can be found in Ref.¹⁹.

III. RESULTS AND DISCUSSION

A. Effect of T on recombination

Figure 2 illustrates the general experimental and simulated LED and PD $I - V$ curves (in a semi-logarithmic scale) corresponding to the best DDS (diameter 0.5 mm) studied in this work, at temperatures 100 K and 300 K. As expected, currents increase with temperature for the same bias, due to a higher carrier population resulting both from increased thermal occupation of electronic states and decrease of the band gap. Additionally, the effect of surface recombination and its variation with temperature can be observed in all curves as a shoulder occurring at currents of 1 and 10 mA, as explained in Ref.¹⁰. These general features of the current-voltage curves allow making several observations, discussed in the next paragraphs. The rest of devices show the same trends but are not included here for the clarity of presentation. On quantitative terms, however, there are small differences such as a small shift in temperature of the peak efficiency, as shown in Fig. 3.

According to simulations and as presented in previous

FIG. 2. Experimental (Exp) and simulated (Sim) $I - V$ curves in semi-logarithmic scale of the LED (I_1) and PD (I_2), measured at 100 K and 300 K, corresponding to the best shown 0.5-mm-diameter device. The other devices show similar behaviour but are not shown for the sake of presentation clarity.

works, the shoulder mentioned above indicates a transition from a surface(mesa edge)-recombination to a bulk- and interface-recombination dominated region^{10,11,18}. The shoulder becomes significantly more visible and shifts to slightly larger currents as temperature increases (see Fig. 2). This suggests that the effect of surface recombination, as well as of other non-radiative recombination mechanisms, is more pronounced at higher temperatures.

B. Effect of T on efficiency

Since the LED internal quantum efficiency (IQE) in the DDS cannot be accessed directly from experiments, we define an experimental figure of merit called the coupling quantum efficiency as $CQE = I_2/I_1$, where I_2 is the photocurrent generated by the short-circuited PD when I_1 is injected into the LED. The CQE combines the LED and PD quantum efficiencies, as well as the optical losses in the structures, and it represents an experimentally-measured lower limit of the IQE . In this work we analyse the behaviour of CQE_{max} , the maximum CQE value that a device can reach at each measured temperature, at a corresponding voltage V_{max} .

Figure 3(a) shows the experimental and simulated values of CQE_{max} as a function of temperature for the DDSs studied in this work. For reference, the figure also shows the CQE_{max} as a function of temperature of a projected DDS with an artificially enhanced IQE , obtained by reducing the surface recombination current in the best 0.5-mm-diameter structure by a factor of 20 (in practice, this could be achieved experimentally by e.g. readily available passivation techniques^{24–26}). The simulated trends of the DDS allow us to understand some of the mechanisms affecting the efficiency of the devices. As can be seen in Fig. 3(a), the optimum temperature T_{max} where the CQE_{max} reaches its maximum occurs below RT for ev-

On the temperature dependence of the efficiency of

every studied device (experimental and simulated). Below CQE_{max} decreases towards 100 K due to a small increase in the surface recombination in the devices mesa edge temperature, as simulations show. Above T_{max} , the CQE goes down due to a decrease of the bulk internal quantum efficiency caused by an interplay of the radiative recombination currents and non-radiative recombination, as suggested by simulated IQE of the LEDs shown in Fig. 3(b) and (c). The IQE of the LED and PD for every measured temperature, as extracted from the simulations, are represented. As seen in Fig. 3 (b) and (c), both IQE s are monotonic functions of temperature, decreasing with increasing temperature for the LED and increasing for the PD. The peak of the CQE is determined by the different temperature dependence of IQE_{LED} and IQE_{PD} that are different for each structure. This result suggests that, in order to observe high CQE in DDSs, and thus observe ELC in the present structure, temperature ranges different from the RT must be explored. The IQE of the LEDs can depend strongly on the extent of surface recombination¹¹. This is especially true for the 1-mm diameter devices, which show a substantial increase in the peak LED IQE from 250 K to 300 K.

Additionally, it is also observed in Fig. 3(a) that CQE_{max} shifts to higher temperatures when the absolute value of the CQE_{max} increases. The two 'identical' external 0.5-mm-diameter devices only differ in their location on the sample, which in principle might cause different structural characteristics due to heterogeneities in the fabrication process. The highest- CQE structure reaches $CQE_{max} \sim 0.61$ at 250 K, whereas the lower- CQE structure reaches $CQE_{max} \sim 0.54$ at 200 K. The same trend is observed when comparing the higher CQE 0.5-mm experimental structure with its simulated high- IQE case: the peak CQE_{max} shifts from 0.61 at 250 K to around 300 K. This suggests that, for that specific device, the highest obtainable CQE could shift towards 300 K.

The devices shown here have not been optimised, and their CQE is lower than what can be achieved for other materials and structures. The best DDS structures so far¹⁸ were different from the structures used here in several aspects: the thickness of the active region was 80 nm (compared to the 300 nm here), which would reduce the surface recombination; the LED barriers were made of AlGaAs, which also allows reducing the surface recombination²⁷; the DDSs contained omnidirectional optical resonators (ODRs), which reduce the optical losses in the cavity of the LED. All these differences led to a $CQE \sim 0.70$ compared to the $CQE \sim 0.60$ presented here. Additionally, in the present work we suspect that a large fraction of the losses in the device originate from the photodetector (see Fig. 3(c) for the simulated PD IQE s), so that the LED internal quantum efficiency is not the limiting factor at high biases¹⁰, as seen in the Fig. 3(b) for low temperatures (below 200 K for the best 0.5-microns-diameter structure).

Additionally, the overall efficiency or power conversion efficiency, PCE , determines the lower limit for the electrical-energy-to-light conversion efficiency of the DDS, which is defined as $PCE = (\hbar\omega/qU) \times CQE$, where $\hbar\omega$ is the aver-

FIG. 3. Experimental (marks) and simulated (lines) temperature dependence of the (a) CQE and (b) PCE maximum values (CQE_{max} and PCE_{max}) for the studied devices. Also shown in red a hypothetical device (HIQE) forced to have a high IQE by minimising the surface recombination of the best 0.5 mm diameter device.

age energy of the emitted photons and can be approximated to $E_g(T) + 3/2k_B T$. ELC is experimentally observed if $PCE > 1$, i.e. $\hbar\omega \times CQE > qU$, corresponding to the case where the net heat absorption overcomes the internal heat generation in the LED.

Figure 4(a) shows the PCE_{max} , the maximum value of the PCE and its experimental and simulated trend for all the measured temperatures and devices. The PCE_{max} shows a peak value for every structure, but unlike the CQE_{max} , the PCE_{max} decreases only little above T_{max} .

The internal PCE of the LED, defined as $PCE_{LED} = (\hbar\omega/qU) \times IQE_{LED}$, represents the overall efficiency of only the LED. Even if the PCE (of the DDS) is below unity, a

This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.5124566

FIG. 4. (a) Experimental and simulated temperature dependence of the DDS PCE_{max} for the experimental (black) and projected (red) structures. (b) Simulated PCE_{LED} maximum values for the same studied structures.

$PCE_{LED} > 1$ suggests there is internal cooling in the LED, although it can not be observed in the DDS. Unlike the PCE , the internal LED PCE cannot be directly measured, but it can be estimated using simulations.

Figure 4(b) shows the simulated PCE_{LED} for all the devices considered. It can be seen that the internal PCE generally peaks at around 200-250 K. Since the PCE_{LED} is defined as $(\hbar\omega/qU) \times IQE_{LED}$, i.e. the bias efficiency times the IQE_{LED} , the trend observed is the result of the interplay between both. In particular, the increase of the PCE_{LED} with increasing temperature below the peak originates from changes in the bias voltage at which the maximum PCE_{LED} happens, while the decrease at temperatures above the peak is caused by the IQE_{LED} . The best experimental (0.5-diameter) DDS structure shows a $PCE \sim 0.55$ at $T = 200$ K, while the corresponding estimated peak value of $PCE_{LED} \sim 0.90$. Additionally, an identical device with a higher IQE and a $PCE_{LED} \gtrsim 1$ at $T \in [200, 250]$, indicates that internal (local) net cooling of the LED could occur by reducing the recombination velocity V_{sr} to 5% of its value for the best device.

In practice this suggests that reaching the cooling threshold for demonstration purposes may be the easiest at around 250 K.

IV. CONCLUSIONS

DDS structures are sensitive to temperature and, generally, it seems that there is a device specific optimal T where the CQE and the PCE are maximised. Hence the measurement temperature provides an additional optimisation possibility when attempting the experimental demonstration of ELC in LEDs. We found that, for the DDS structures with $Al_{0.3}Ga_{0.7}As$ barrier layers LEDs studied in this work, it is typically possible to observe higher CQE values at temperatures T_{max} below RT. However, the CQE_{max} peak additionally shifts to higher T as the CQE itself increases, due to the effect of the improved PD $IQEs$.

In consequence, the DDS PCE remains constant above the T_{max} , but numerical simulations suggest that the PCE_{LED} of an optimised LED with a high IQE (obtained by a projected minimised surface recombination velocity) would reach values slightly above unity at temperatures below RT, indicating that the LED would locally experience cooling, even with a relatively low CQE . To demonstrate high efficiency devices capable of ELC it is necessary to minimize non-radiative recombination, maximize light extraction and use very high quality materials. Furthermore, in order to directly observe ELC it is also necessary to thermally insulate the LED from its surroundings, e.g. by producing stand-alone LEDs with extremely high light extraction efficiency or thermophotonic devices integrating transparent thermal insulators between the LED and its light absorbing surroundings.

ACKNOWLEDGMENTS

This project has received funding from the Academy of Finland and the European Research Council (ERC) under the European Unions Horizon 2020 research and innovation programme (grant agreement No 638173). We acknowledge the provision of facilities and technical support by Aalto University at Micronova Nanofabrication Centre. We also acknowledge Camilla Tossi and Prof. Ilkka Tittonen for allowing access to the cryostat used for the measurements.

BIBLIOGRAPHY

- ¹K. Lehovec, C. A. Accardo, and E. Jamgochian, "Light emission produced by current injected into a green silicon-carbide crystal," *Physical Review* **89**, 20–25 (1953).
- ²R. J. Keyes and T. M. Quist, "Recombination radiation emitted by gallium arsenide," *Proc. IRE* **50**, 1822–1823 (1962).
- ³E. F. Schubert, *Light-emitting diodes* (2003).
- ⁴P. Santhanam, D. Huang, D. J. Gray, and R. J. Ram, "Electro-luminescent cooling: light emitting diodes above unity efficiency," (San Francisco, California, USA, 2013) p. 863807.
- ⁵G. Min and D. Rowe, "Conditions for observing the thermo-electro-photo cooling effect," *IET Science, Measurement & Technology* **1**, 329–332 (2007).
- ⁶O. Heikkilä, J. Oksanen, and J. Tulkki, "Ultimate limit and temperature dependency of light-emitting diode efficiency," *Journal of Applied Physics* **105**, 093119 (2009).

This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.5124566

- ⁷J. Piprek and Z.-M. Li, "Electroluminescent cooling mechanism in InGaN/GaN light-emitting diodes," *Optical and Quantum Electronics* **48**, 472 (2016).
- ⁸J. Xue, Z. Li, and R. J. Ram, "Irreversible thermodynamic bound for the efficiency of light-emitting diodes," *Physical Review Applied* **8** (2017), 10.1103/PhysRevApplied.8.014017.
- ⁹P. Santhanam, D. J. Gray, and R. J. Ram, "Thermoelectrically pumped light-emitting diodes operating above unity efficiency," *Physical Review Letters* **108**, 097403 (2012).
- ¹⁰I. Radevici, J. Tiira, T. Sadi, S. Ranta, A. Tukiainen, M. Guina, and J. Oksanen, "Thermophotonic cooling in GaAs based light emitters," *Applied Physics Letters* **114** (2019).
- ¹¹T. Sadi, I. Radevici, P. Kivisaari, and J. Oksanen, "Electroluminescent Cooling in III-V Intracavity Diodes: Practical Requirements," *IEEE Trans. Electron Devices* **66**, 963–968 (2019).
- ¹²C. A. Hurni, A. David, M. J. Cich, R. I. Aldaz, B. Ellis, K. Huang, A. Tyagi, R. A. DeLille, M. D. Craven, F. M. Steranka, and M. R. Krames, "Bulk GaN flip-chip violet light-emitting diodes with optimized efficiency for high-power operation," *Applied Physics Letters* **106**, 031101 (2015).
- ¹³Y.-H. Choi, G.-H. Ryu, and H.-Y. Ryu, "Evaluation of the temperature-dependent internal quantum efficiency and the light-extraction efficiency in a GaN-based blue light-emitting diode by using a rate equation model," *Journal of the Korean Physical Society* **69**, 1286–1289 (2016).
- ¹⁴J. H. Park, J. W. Lee, D. Y. Kim, J. Cho, E. F. Schubert, J. Kim, J. Lee, Y.-I. Kim, Y. Park, and J. K. Kim, "Variation of the external quantum efficiency with temperature and current density in red, blue, and deep ultraviolet light-emitting diodes," *Journal of Applied Physics* **119**, 023101 (2016).
- ¹⁵S. Lin, T. Shih, W. Yan, Y. Lu, Y. Lin, R. R. Chang, and Z. Chen, "Maximum limits on external quantum efficiencies in bare LEDs," *IEEE Transactions on Electron Devices* **64**, 1597–1601 (2017).
- ¹⁶T. P. Xiao, K. Chen, P. Santhanam, S. Fan, and E. Yablonovitch, "Electroluminescent refrigeration by ultra-efficient GaAs light-emitting diodes," *Journal of Applied Physics* **123**, 173104 (2018).
- ¹⁷A. Olsson, J. Tiira, M. Partanen, T. Hakkarainen, E. Koivusalo, A. Tukiainen, M. Guina, and J. Oksanen, "Optical energy transfer and loss mechanisms in coupled intracavity light emitters," *IEEE Transactions on Electron Devices* **63**, 3567–3573 (2016).
- ¹⁸I. Radevici, J. Tiira, T. Sadi, and J. Oksanen, "Influence of photo-generated carriers on current spreading in double diode structures for electroluminescent cooling," *Semiconductor Science and Technology* **1**, 05LT01–1–5 (2018), DOI: 10.1088/1361-6641/aab6c3.
- ¹⁹T. Sadi, I. Radevici, P. Kivisaari, and J. Oksanen, "Electroluminescent Cooling in III-V Intracavity Diodes: Efficiency Bottlenecks," *IEEE Trans. Electron Devices* **66**, 2651–2656 (2019).
- ²⁰P. Kivisaari, J. Oksanen, J. Tulkki, and T. Sadi, "Monte Carlo simulation of hot carrier transport in III-N LEDs," *Journal of Computational Electronics* **14**, 382–397 (2015).
- ²¹M. Sotoodeh, A. H. Khalid, and A. A. Rezazadeh, "Empirical low-field mobility model for iii–v compounds applicable in device simulation codes," *J. Appl. Phys.* **87**, 2890–2900 (2000).
- ²²Y. Varshni, "Temperature dependence of the energy gap in semiconductors," *Physica* **34**, 149–154 (1967).
- ²³M. Levinshtein, S. Rumyantsev, and M. Shur, *Ternary And Quaternary III-V Compounds, Handbook Series on Semiconductor Parameters* (World Scientific Publishing, 1999).
- ²⁴A. G. Baca and C. I. H. Ashby, *Fabrication of GaAs Devices* (The Institution of Engineering and Technology, 2005).
- ²⁵A. Aierken, *Passivation of GaAs surfaces and fabrication of self-assembled In(Ga)As/GaAs quantum ring structures*, Ph.D. thesis, Aalto University (2008).
- ²⁶Y. Wada and K. Wada, "Gaas surface passivation by deposition of an ultrathin inp-related layer," *Appl. Phys. Lett.* **63**, 379–381 (1993), DOI: 10.1063/1.110049.
- ²⁷T. Sadi, I. Radevici, P. Kivisaari, A. Casado, and J. Oksanen, "Effect of interface recombination on the efficiency of intracavity double diode structures," *Optical and Quantum Electronics* **51**, 207 (2019).

This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.
PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.5124566

This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.
PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.5124566

This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.
PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.5124566

This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.
PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.5124566