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ABSTRACT

We report the demonstration of hybrid-cladding interband cascade lasers (ICLs) for a room temperature emission wavelength range from 2.68 to $2.9\ \mu\text{m}$. Their threshold current density and threshold input power density are substantially lower than previously reported values from superlattice-cladding ICLs at similar wavelengths. These ICLs were able to operate in pulsed modes at temperatures close to $400\ \text{K}$. At $300\ \text{K}$, the threshold current density was as low as $191\ \text{A}/\text{cm}^2$ with a threshold input power density of $693\ \text{W}/\text{cm}^2$. Narrow ridge devices lased in a continuous wave (cw) mode at room temperature and above with threshold current density and output power that are improved compared to previous ICLs at similar wavelengths. Comparative studies of devices with different local material qualities from the same wafer and different wafers revealed a certain correlation between Shockley–Read–Hall recombination and threshold current density, which shed light on understanding the degradation of device performance with the shortening of the lasing wavelength of type-II ICLs. Additionally, negative differential conductance features were observed under reverse bias voltage, which may provide an interesting and potentially useful means to examine the material and fabrication qualities of devices with some extended applications.

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I. INTRODUCTION

Since the original proposal in 1994,¹ interband cascade lasers (ICLs) based on type-II quantum well (QW) active regions have been advanced remarkably^{2–9} by taking advantage of the broken-gap alignment in III–V Sb-based heterostructures.^{10,11} Type-II ICLs can cover a wide wavelength range from below $3\ \mu\text{m}$ to beyond $14\ \mu\text{m}$.^{4–9,12–14} Particularly in the 3 – $6\ \mu\text{m}$ wavelength region, they can be operated in a continuous wave (cw) mode at room temperature (RT) and above with a low threshold input power density, which is very favorable for many applications that require low power consumption. However, when the emission wavelength (λ) is below $3\ \mu\text{m}$, the threshold current density (J_{th}) of type-II ICLs increases rapidly (e.g., $>230\ \text{A}/\text{cm}^2$ at $300\ \text{K}$) with decreasing λ for unknown reasons.^{4,6} The best device performance of type-II ICLs with traditional superlattice (SL) cladding layers as shown Fig. 1(a),

in terms of the lowest RT J_{th} and threshold input power density (P_{th}), was achieved near $3.6\ \mu\text{m}$.^{4,6} Recently, by employing a hybrid-cladding configuration¹⁵ that includes highly doped semiconductor layers on a GaSb substrate as shown in Fig. 1(b), we have demonstrated type-II ICLs with the lowest threshold input power density of $312\ \text{W}/\text{cm}^2$ and a high voltage efficiency of 82% at $300\ \text{K}$ for an emission wavelength of $3.3\ \mu\text{m}$,¹⁶ which altered the long-held optimal wavelength of $3.6\ \mu\text{m}$. In addition, another group demonstrated the lowest threshold density of $95\ \text{A}/\text{cm}^2$ from a top hybrid-cladding ICL at $25\ ^\circ\text{C}$ for an emission wavelength of $3.5\ \mu\text{m}$.¹⁷ As a highly doped InAsSb layer has higher thermal and electrical conductivities and a lower refractive index than the part of the SL cladding that it replaced, the hybrid-cladding ICLs can have enhanced optical confinement and better thermal dissipation with reduced device thickness and improved voltage efficiency compared to traditional ICLs with the SL cladding. These

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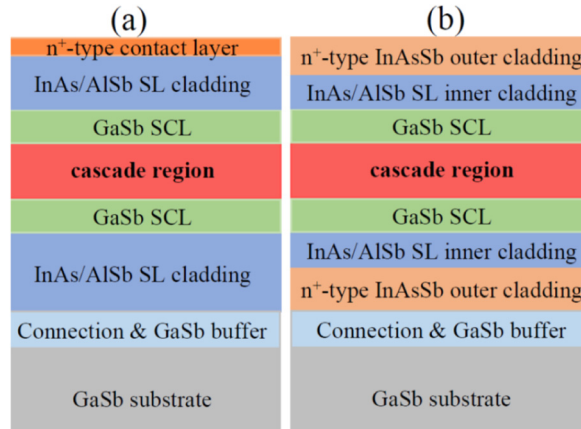


FIG. 1. Schematic illustration of ICLs with (a) SL and (b) hybrid cladding configurations.

advantages were validated at least partially by the recent results of the hybrid-cladding ICLs with longer emission wavelengths ($\geq 3.3 \mu\text{m}$).^{16,17} This suggests that hybrid-cladding may substantially improve type-II ICL performance at emission wavelengths below $3 \mu\text{m}$ and help to understand why the device performance degrades with shortening the wavelength, which would need to be examined experimentally.

In this work, by growing hybrid-cladding type-II ICL structures for emission at shorter wavelengths and investigating devices made from them, we demonstrated significantly improved device performance with substantially reduced J_{th} and P_{th} for emission wavelengths below $3 \mu\text{m}$ at 300 K. Additionally, a correlation between threshold current density and local material quality was discovered. Furthermore, negative differential conductance features were observed from these ICL devices under reverse bias at temperatures up to 380 K.

II. MATERIAL GROWTH AND DEVICE FABRICATION

The six-stage ICL wafers Y092, Y093A, and Y093B were grown by molecular beam epitaxy using a Veeco GENxplor with As and Sb supplied from valved cracking sources. The active region for all three wafers was designed with the W-QW^{11,18,19} layer sequence of AlSb/InAs/Ga_{0.65}In_{0.35}Sb/InAs/AlSb (26/13.8/28/11.7/12 Å) in the growth direction for achieving RT lasing near $2.9 \mu\text{m}$, which is modified from the previous ICL structure¹⁶ with a RT emission wavelength of $3.3 \mu\text{m}$. The six cascade stages were sandwiched between two 300 nm-thick Te-doped GaSb ($1.2 \times 10^{17} \text{ cm}^{-3}$ for Y092 and two 50 nm-thick side region of Y093, in which the center region was doped at $1.1 \times 10^{16} \text{ cm}^{-3}$) separate confinement layers (SCLs), two InAs/AlSb SL inner cladding layers and two highly doped n⁺-InAsSb outer cladding layers. The four center InAs layers of the electron injector were doped with Si to $4.5 \times 10^{18} \text{ cm}^{-3}$ for carrier-rebalance considerations.² The only difference in design between wafers Y092 and Y093 (A and B) is the doping in the GaSb SCLs. They were grown with a relatively long separation in

time (3 months), while Y093A (on a quarter 2 in. substrate) and Y093B (on a whole 2 in. substrate) have identical design and were grown with a short time interval (1 day).

The material quality of the three ICL wafers was characterized by high-resolution x-ray diffraction, and their surface morphology was characterized by differential interference contrast (DIC) microscopy. Sharp x-ray diffraction peaks were observed from all three wafers, indicating very good structural quality. According to the positions of the satellite peaks, the SL period and the thickness of the cascade regions were within 2.3% and 1.5% of the design values, respectively, for all three wafers. The positions of the zeroth-order peak for the cascade regions were slightly different among all three wafers, which is consistent with slightly different emission wavelengths. From surface images on the three wafers, the average surface defect density was $1.15 \times 10^4 \text{ cm}^{-2}$ for Y092, $6.34 \times 10^3 \text{ cm}^{-2}$ for Y093 A, and $1.09 \times 10^4 \text{ cm}^{-2}$ for Y093B, based on which Y093 A is the best. A piece of each wafer was fabricated into $100 \mu\text{m}$ -wide and $150 \mu\text{m}$ -wide broad area (BA) mesas using wet chemical etching and standard ultraviolet contact photolithography. The pieces were then cleaved into laser bars with a cavity length of $\sim 2 \text{ mm}$. The substrates were neither thinned nor were the facets coated. The laser bars were mounted epi-side up on copper heat sinks for testing.

III. DEVICE PERFORMANCE, ELECTRICAL CHARACTERISTICS, AND DISCUSSION

A. Device performance

The BA devices lased in both cw and pulsed modes. As shown by the emission spectra in Fig. 2(a), a $100 \mu\text{m} \times 2 \text{ mm}$ device from Y092 lased in a pulsed mode at temperatures up to 397 K with a threshold current (I_{th}) of 3.5 A ($J_{\text{th}} \sim 1.75 \text{ kA/cm}^2$) at an emission wavelength (λ) near $3.05 \mu\text{m}$, which was redshifted from $2.75 \mu\text{m}$ at 202 K. At 300 K, the device had a J_{th} of 191 A/cm^2 for a lasing wavelength of $2.9 \mu\text{m}$ and with a threshold voltage (V_{th}) of 3.63 V, corresponding to a voltage efficiency (η_v) of 71%. The threshold

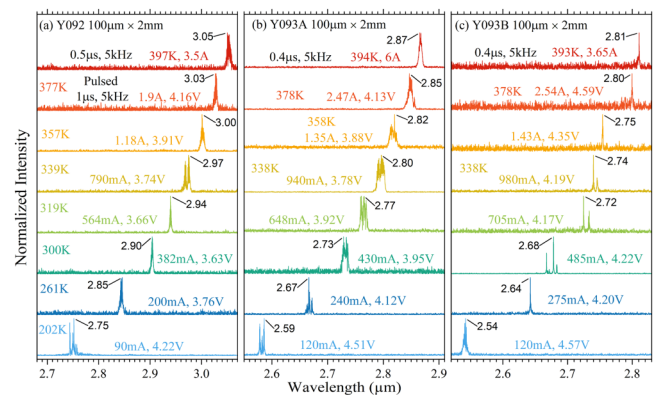


FIG. 2. Pulsed lasing spectra for three $100 \mu\text{m} \times 2 \text{ mm}$ ICLs from (a) Y092, (b) Y093A, and (c) Y093B along with their operating currents, voltages, and emission wavelengths at each operating temperature.

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voltage is higher than expected with a reduced voltage efficiency compared to our previous hybrid-cladding ICLs,¹⁶ which might be caused by a thin oxide layer formed on the surface of the top layer of InAsSb through air exposure before the metal contact was deposited. A $100\text{ }\mu\text{m} \times 2\text{ mm}$ device from Y093A lased in the pulsed mode at temperatures up to 394 K with a threshold current (I_{th}) of 6 A ($J_{\text{th}} \sim 3\text{ kA/cm}^2$) at an emission wavelength near $2.87\text{ }\mu\text{m}$, which was redshifted from $2.59\text{ }\mu\text{m}$ at 202 K as shown in Fig. 2(b). At 300 K, the device had a J_{th} of 215 A/cm^2 for a lasing wavelength of $2.73\text{ }\mu\text{m}$ and with a V_{th} of 3.95 V, corresponding to a η_v of 69%. A $150\text{ }\mu\text{m} \times 2\text{ mm}$ device from Y093A lased in the pulsed mode at 300 K with a J_{th} of 195 A/cm^2 for a lasing wavelength of $2.737\text{ }\mu\text{m}$ and with a V_{th} of 3.785 V, corresponding to a η_v of 72%, which was a better performance than the $100\text{ }\mu\text{m}$ -wide device due to possibly reduced sidewall leakage. The lasing wavelengths of devices from Y093A were shorter with higher J_{th} and V_{th} compared to the devices from Y092. The observed emission wavelengths of devices from Y093B were the shortest for type-II ICLs with somewhat higher J_{th} as shown by the pulsed lasing spectra of a $100\text{ }\mu\text{m} \times 2\text{ mm}$ device in Fig. 2(c) compared to devices from Y093A. For example, at 300 K, the pulsed lasing wavelength was $2.68\text{ }\mu\text{m}$ with a J_{th} of 243 A/cm^2 and a V_{th} of 4.22 V, corresponding to a η_v of 66%. This could be caused by the slightly different cascade regions indicated by the x-ray diffraction pattern and the higher threshold voltage inducing a greater blueshift with increased J_{th} due to the higher surface defect density in Y093B compared to Y093A.

The values of J_{th} ($\geq 191\text{ A/cm}^2$) are significantly higher than that (114 A/cm^2) for our reported RT hybrid-cladding ICL at $3.3\text{ }\mu\text{m}$,¹⁶ confirming the performance degradation trend of type-II ICLs with decreasing lasing wavelength.^{4,6} However, they are substantially lower than the J_{th} values for previous seven-stage SL-cladding ICLs at similar wavelengths reported by the Naval Research Laboratory (NRL)^{4,6} as shown in Fig. 3. Additionally,

their threshold input power densities ($P_{\text{th}} = J_{\text{th}} \times V_{\text{th}}$) are reduced significantly compared to SL-cladding ICLs at similar emission wavelengths as shown in Fig. 3. For example, the P_{th} of 693 W/cm^2 for the hybrid-cladding ICL at a RT emission wavelength of $2.9\text{ }\mu\text{m}$ is reduced to a half of that for a SL-cladding ICL at an emission wavelength of $2.92\text{ }\mu\text{m}$ and still notably lower than values for SL-cladding ICLs at longer wavelengths near $3.0\text{--}3.1\text{ }\mu\text{m}$. The reduction of J_{th} and P_{th} is even greater for the RT hybrid-cladding ICL near $2.74\text{ }\mu\text{m}$ compared to the previously reported ICL at a similar wavelength ($2.78\text{ }\mu\text{m}$). Also included in Fig. 3 is a recent SL-cladding five-stage ICL near $2.77\text{ }\mu\text{m}$ reported by a group at the University of Montpellier (UM),²⁰ which is much better than the previously reported ICL at a similar wavelength ($2.78\text{ }\mu\text{m}$) in terms of its J_{th} and P_{th} at 20°C , but not as good as the hybrid-cladding ICL near $2.74\text{ }\mu\text{m}$ reported in this work. These results suggest that type-II ICLs have not been optimized in the emission wavelength region below $3\text{ }\mu\text{m}$ and there is room for further improvement.

In cw operation, the $100\text{ }\mu\text{m} \times 2\text{ mm}$ device from Y092 lased at temperatures up to 240 K with a J_{th} of 167.5 A/cm^2 near $2.88\text{ }\mu\text{m}$, which was redshifted from $2.57\text{ }\mu\text{m}$ at 80 K as shown in Fig. 4(a). The maximum cw operating temperature of this device was limited mainly by relatively poor thermal management as this J_{th} of 167.5 A/cm^2 was below the limit ($>200\text{ A/cm}^2$) for a typical BA ICL. This device could likely operate in the cw mode a few degrees above 240 K as its output power was higher than 3 mW/facet at 240 K as shown by its current–voltage–light (IVL) characteristics in Fig. 5. At 80 K, its slope efficiency of $\sim 0.6\text{ W/A}$ per facet corresponds to an external quantum efficiency (EQE) of 249% for two facets, which implies the feasibility of a cw output power exceeding 200 mW/facet at a large current (e.g., 500 mA). Its EQE gradually decreased with increasing operating temperature to 220 K and then dropped rapidly at a higher temperature with more current induced heating as shown in Fig. 5. The $100\text{ }\mu\text{m} \times 2\text{ mm}$ device from Y093A lased in the cw mode at temperatures up to

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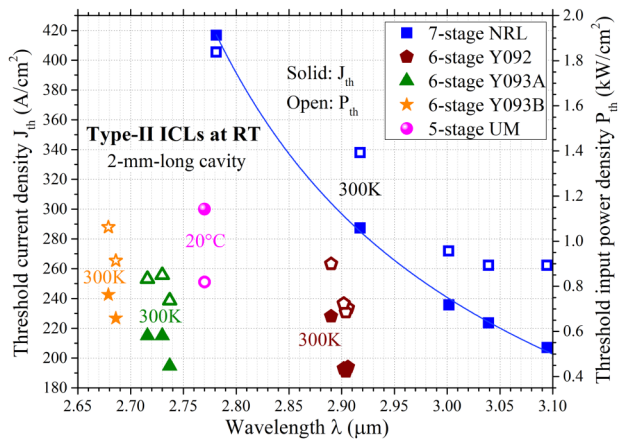


FIG. 3. Threshold current density J_{th} and input power density P_{th} for 2 mm-long type-II ICLs at RT reported in this work (Y092, Y093A, and Y093B) and by NRL and UM. The blue line shows an increased trend of J_{th} for SL-cladding ICLs with decreasing λ .

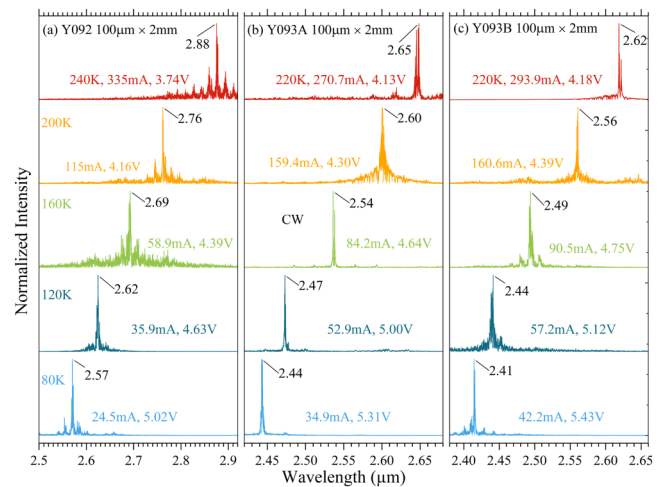


FIG. 4. The cw spectra for three $100\text{ }\mu\text{m} \times 2\text{ mm}$ ICLs from (a) Y092, (b) Y093A, and (c) Y093B.

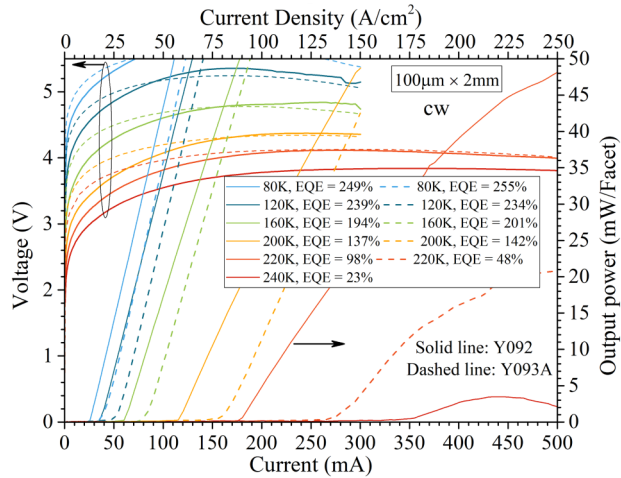


FIG. 5. The cw IVL characteristics for two $100\mu\text{m} \times 2\text{mm}$ ICLs from Y092 (solid) and Y093A (dashed).

220 K with a J_{th} of 135 A/cm^2 near $2.65\mu\text{m}$, which was redshifted from $2.44\mu\text{m}$ at 80 K as shown in Fig. 4(b). Compared to Y092, the cw lasing wavelength of Y093A was shorter with higher J_{th} and V_{th} , resulting in a lower maximum cw operating temperature. However, its EQE at 80 K was somewhat higher as shown in Fig. 5, which may be attributed to a reduced internal loss with less free-carrier absorption at the shorter wavelength and the lower doping in the SCLs. Their differences in EQE at high temperatures ($\geq 220\text{ K}$) became significant as heating was substantial with higher J_{th} in Y093A as shown in Fig. 5. The $100\mu\text{m} \times 2\text{mm}$ device from Y093B lased in the cw mode with shorter emission wavelengths, higher J_{th} and V_{th} in the temperature range from 80 to 220 K as shown in Fig. 4(c) compared to Y093A. Especially at 80 K, J_{th} was 21% higher, suggesting possibly more Shockley-Read-Hall (SRH) recombination due to more defects compared to Y093A. However, its EQEs, extracted from measured cw current-light characteristics (not shown here), are very similar to Y093A in a wide temperature range from 80 to 200 K, suggesting nearly unchanged internal absorption loss although their J_{th} and V_{th} had visible differences as shown in Figs. 3 and 4. As Y093A and Y093B were based on the same ICL structure, their differences in J_{th} might be caused mainly by material quality as reflected by the surface defect density. This conjecture is supported by the following analysis and discussion on devices made from different locations of Y092.

Figure 3 includes RT J_{th} and P_{th} for three additional BA ICLs made from wafer Y092 at different locations. An ICL near the edge of the wafer exhibited a higher J_{th} of 228 A/cm^2 and a P_{th} of 900 W/cm^2 , while the other two had similar J_{th} and P_{th} , indicating some variations of device performance across the wafer due to non-uniformities of material quality. To examine more of their properties, cw IVL characteristics for two $150\mu\text{m} \times 2\text{mm}$ ICLs in Fig. 3 with different J_{th} are plotted together in Fig. 6 for comparison. The two $150\mu\text{m}$ -wide devices exhibited comparable EQEs in a temperature range from 80 to 200 K although they had significantly

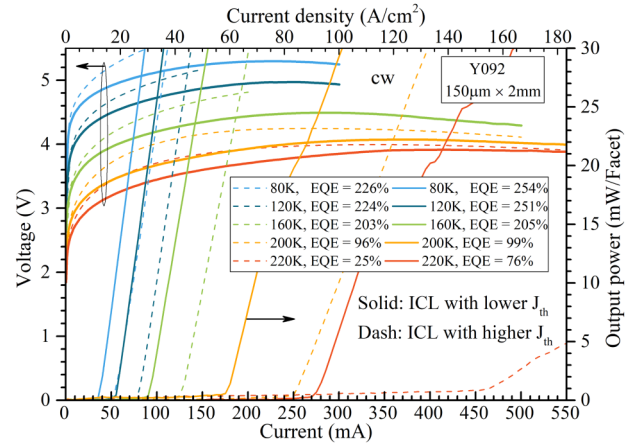


FIG. 6. The cw IVL characteristics for two $150\mu\text{m} \times 2\text{mm}$ ICLs from Y092 with different local material qualities.

different J_{th} . Their EQEs were also similar to what was observed in the $100\mu\text{m}$ -wide device in the same temperature range as shown in Fig. 5. There were some noticeable differences in EQE at high temperatures due to substantial heating with large currents. Considering possible variations and uncertainties in beam alignment for individual devices during the measurements, as well as negligible current-dependent absorption loss due to inter-valence-subband transitions at this short emission wavelength,⁷ the internal absorption loss could approximately be the same in these devices despite different J_{th} values. Additionally, the EQE for these short-wavelength ICLs at low temperatures is similar to reported values of previous ICLs with a RT emission wavelength near $3.3\mu\text{m}$ ¹⁶ and $3.6\mu\text{m}$.²¹ These data imply that the internal absorption loss does not increase when the lasing wavelength decreases. However, the lowest J_{th} obtained from these short-wavelength ICLs at 80 K was 12.3 A/cm^2 , which is higher than 6.95 A/cm^2 for the $3.3\mu\text{m}$ ICL at 80 K and much higher than $\sim 2\text{ A/cm}^2$ for InAs-based ICLs at 80 K with longer emission wavelengths ($>4\mu\text{m}$).⁵ Hence, the increase of J_{th} in short-wavelength ICLs could be caused by an increased SRH recombination rate that may be related to not only defect density but also the relative position of defect levels in the bandgap, as well as the overlap of electron and hole spatial distributions as reflected by performance features of Si-based ICLs.²² When the QW active region is adjusted to achieve lasing at a shorter wavelength, the relative position of defect levels in the bandgap is changed and the overlap of electron and hole spatial distributions is increased, which may result in the increased SRH recombination. This speculated mechanism will need to be further investigated.

In Fig. 7, the pulsed IVL characteristics were plotted for the $150\mu\text{m} \times 2\text{mm}$ ICL from Y092 with the lower J_{th} in the temperature range from 200 to 360 K. The EQE decreased gradually with operating temperature (T) when heating effects could be ignored. At 300 K, the extracted EQE was 208%, corresponding to $\sim 35\%$ per stage. However, the reported value of EQE is conservative without accounting for the beam divergence loss, which might be

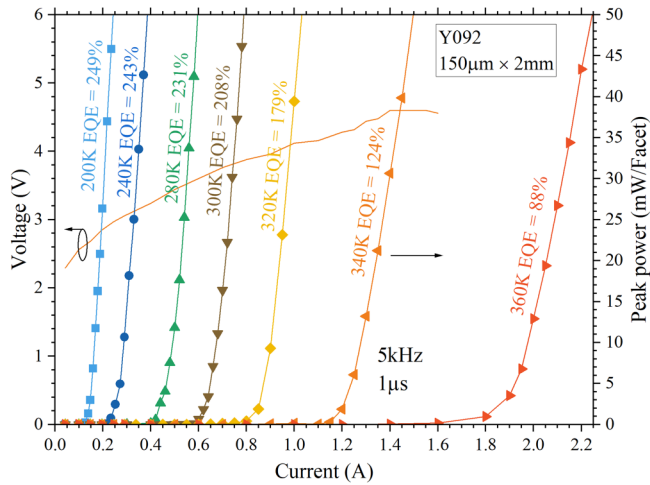


FIG. 7. The pulsed IVL characteristics for the $150\mu\text{m} \times 2\text{mm}$ ICL operating from 200 to 360 K.

20%–30%. Hence, the actual EQE per stage may exceed 40% at 300 K, which is somewhat higher than previously reported values ($\sim 38\%$ – 40% per stage) for SL-cladding ICLs at similar emission wavelengths.⁶ The EQE extracted from pulsed IVL characteristics of the device from Y093A in a wide temperature range is similar to that from Y092, supporting the conclusion of no increase in the internal absorption loss with shortening emission wavelength.

The temperature-dependent threshold current density, threshold voltage, lasing wavelength near threshold, and voltage efficiency are summarized in Fig. 8 for four representative devices from Y092. The two devices near the edge of the wafer had higher J_{th} and V_{th} with lower voltage efficiency compared to devices away from the edge. The differences are particularly visible at low temperatures (e.g., 80 K), indicating distinctive SRH recombination rates. In addition, their lasing wavelengths were slightly shorter and had either a blueshift or a bending downward at high operating temperatures near 400 K as shown in Fig. 8. This suggests that they were approaching the maximum limit of operating temperature. However, the lasing wavelength of the devices away from the edge always redshifted with increasing operating temperature, implying the possibility of higher operating temperatures for these devices. Their pulsed lasing temperature was restricted mainly by heating with high current and the limitation of the current source used. These differences in J_{th} , V_{th} , and lasing wavelength between individual devices at different locations with different sizes revealed some correlations between device performance and local material quality that was mainly related to SRH recombination.

Although J_{th} increased for ICLs at the shorter wavelengths, their characteristic temperature T_0 of about 57 K in the temperature range from 280 to 360 K was slightly higher than the previously reported value of 56 K for the longer wavelength ICLs with similar structures.^{16,21} The higher value of T_0 might be related to increased SHR recombination at the shorter wavelengths, which is relatively insensitive to temperature. Analysis of the temperature-dependent

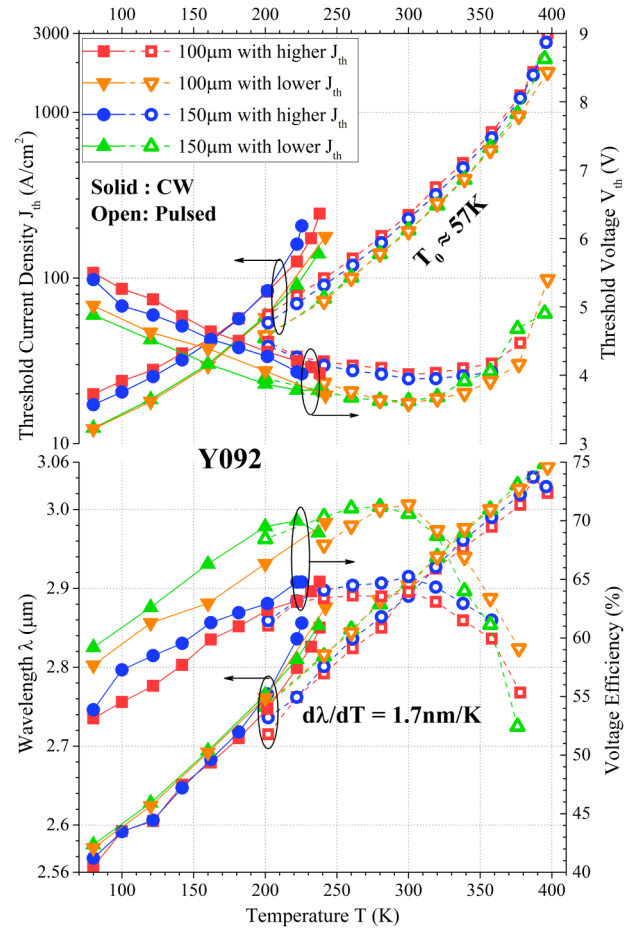


FIG. 8. Threshold current density, threshold voltage, lasing wavelength, and voltage efficiency vs temperature for four BA ICLs from Y092.

threshold current density, threshold voltage, lasing wavelength near threshold, and voltage efficiency for devices from Y093A and Y093B showed similar behaviors. For example, lasing wavelengths for devices from both Y093A and B increased with temperature at a rate of 1.62 nm/K and their J_{th} rose with temperature with a characteristic temperature T_0 of 57 and 59 K for $150\mu\text{m}$ -wide and $100\mu\text{m}$ -wide devices, respectively. In comparison, devices from Y093B had higher J_{th} and V_{th} with shorter emission wavelengths than devices from Y093A, following the general trend of type-II ICLs when emission wavelengths are shortened below $3.1\mu\text{m}$, as shown in Fig. 3. However, the increase in J_{th} with a decrease in emission wavelength for these recent hybrid-cladding ICLs is much smaller than what was observed previously for SL-cladding ICLs, which also depends on the material quality related to SRH recombination. Additionally, unlike the highest voltage efficiency near 280 K for Y092, the highest voltage efficiency of 75% for Y093 A was near 350 K related to the shorter wavelength, implying potential for an optimization to minimize the threshold power density at RT.

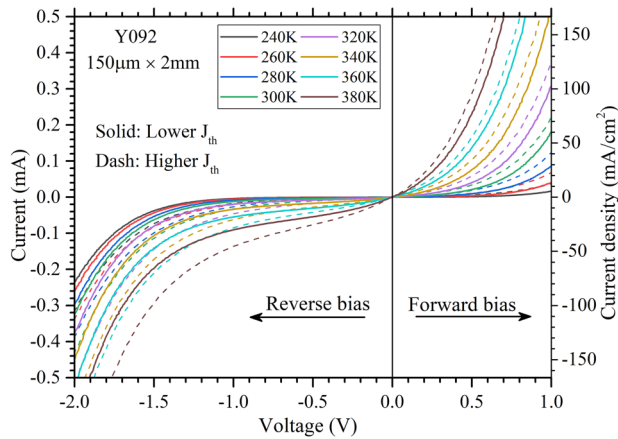


FIG. 9. The DC IV characteristics for the two ICLs from Y092 under both forward and reverse bias voltages.

B. Electrical characteristics

To further investigate the correlation between the local material quality and device performance, devices were operated under both DC forward and reverse bias voltages. Figure 9 shows the DC voltage–current characteristics of the two 150- μm -wide ICLs (from Y092) that have different J_{th} as shown in Figs. 6 and 8. Under relatively low bias voltages in either direction, both exhibited asymmetric diode rectifying features at temperatures up to 380 K, indicating reasonable material quality. However, there are substantial differences in current between the two devices under a fixed voltage. For example, at 300 K, the relative difference is about 19% under a forward voltage of 1 V. This indicates that the carrier lifetime is shorter in the device with the higher current. Because Auger recombination is less significant under a small current injection (≤ 0.3 mA at 300 K, corresponding to a current density of 100 mA/cm^2), SRH recombination could be dominant and faster in the device with a shorter carrier lifetime. Consequently, the threshold current density is higher in the device with the faster SRH recombination. This is consistent with the higher reverse current due to a related shorter SRH generation time under a small reverse bias, as shown in Fig. 9. When the reverse bias voltage was higher than a certain point, the reverse current increased rapidly, which was caused by electron tunneling through the hole injector, i.e., the electron barrier (eB) composed of two GaSb/AlSb QWs. With a further increase in the reverse bias voltage, sawtooth characters, corresponding to negative differential conductance (NDC) features, appeared, as shown in Fig. 10. The six NDC features, one for each of the six cascade stages, could clearly be identified at temperatures up to 340 K. At higher temperatures, some NDC features became plateaus and then disappeared. The NDC features were due to resonant tunneling through six eBs and sequential turning off of the resonant tunneling, similar to what was observed in interband cascade infrared photodetectors (ICIPs).²³ The difference is where the electrons come from. In an ICL, the electrons were mainly from the relatively highly doped n-type electron injectors and are

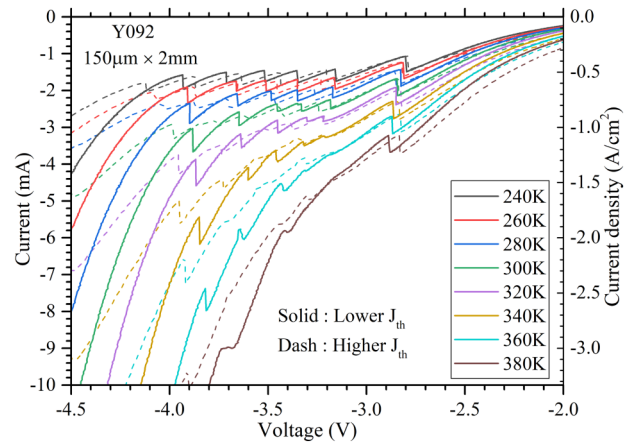


FIG. 10. The DC IV characteristics for the two 150- μm -wide ICLs under large reverse bias voltages scanned from -4.5 to -2.0 V.

majority carriers, while electrons in an ICIP were primarily from p-type absorber regions and are minority carriers. Consequently, their temperature dependences are different. In an ICL, the NDCs were more distinguishable at lower temperatures, but still visible at high temperatures such as 380 K, which is interesting and deserves more systematic study in the future. Comparing two devices with different material qualities and related carrier lifetimes, the NDC features were considerably sharper and more sustainable at high temperatures in the device with the lower J_{th} . This is consistent with the better material quality associated with the longer carrier lifetime, which implies narrower quasi-bound energy levels in QWs for resonant tunneling.

To expand this investigation, DC IV characteristics were measured for a six-stage ICL from an earlier reported wafer Y088²¹ with an emission wavelength of $3.62 \mu\text{m}$ at 300 K. Figure 11 compares the IV characteristics for this device with those of the Y092 device measured in Figs. 7 and 10, which emitted at $2.9 \mu\text{m}$. This $3.6 \mu\text{m}$ ICL at 300 K had a J_{th} of 152 A/cm^2 , substantially lower than that for the $2.9 \mu\text{m}$ ICL. At a fixed voltage, because of the narrower bandgap, the current in the $3.6 \mu\text{m}$ ICL was significantly higher than in the $2.9 \mu\text{m}$ ICL. However, they operated at very different voltages and the difference ΔV_{th} in threshold voltage should at least equal to $\Delta E_p N_s / e$ (~ 0.51 V at 300 K) in an ideal case, where ΔE_p is the energy difference of emitted photons, N_s is the number of cascade stages, and e is the electron charge. The measured ΔV_{th} of ~ 1 V at 300 K was larger than $\Delta E_p N_s / e$ due to the higher J_{th} in the $2.9 \mu\text{m}$ ICL. As a comparison, the injection current $I_{Y092}(V_f + \Delta V_{\text{th}})$ in the $2.9 \mu\text{m}$ ICL was higher than $I_{Y088}(V_f)$ in the $3.6 \mu\text{m}$ ICL under a forward bias voltage V_f as shown in Fig. 11. This behavior is consistent with possibly increased SRH recombination in the $2.9 \mu\text{m}$ ICL under a larger forward bias, causing a substantially higher J_{th} than in the $3.6 \mu\text{m}$ ICL. Under reverse bias voltages as shown in Fig. 11, the $3.6 \mu\text{m}$ ICL exhibited six NDC features at each operating temperature with higher peak-to-valley current ratios (e.g., ~ 1.9 at 300 K) compared to the $2.9 \mu\text{m}$ ICL. Owing to the narrower bandgap, these NDC features appeared

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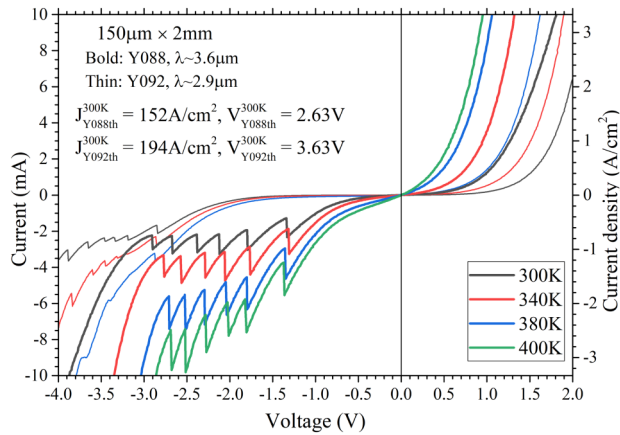


FIG. 11. The DC IV characteristics for two 150 μm -wide ICLs with different lasing wavelengths.

under relatively low reverse bias voltages and were still clearly visible at 400 K.

DC IV characteristics were measured for two 150 μm -wide ICLs from Y093A and Y093B, respectively, as shown in Fig. 12. They exhibited asymmetric diode rectifying features in a wider voltage range and had a smaller current density at a given voltage compared to ICLs from Y092 and previously reported wafers.^{16,21} This implies that their bandgaps are greater, consistent with their shorter emission wavelengths. At every operating temperature, the injection current was clearly lower in the device from Y093B than from Y093A, indicating the larger bandgap of Y093B with the observed shortest emission wavelength than that of Y093A. However, they operated at different voltages for lasing action, as discussed above. For example, at 300 K, the threshold voltage for

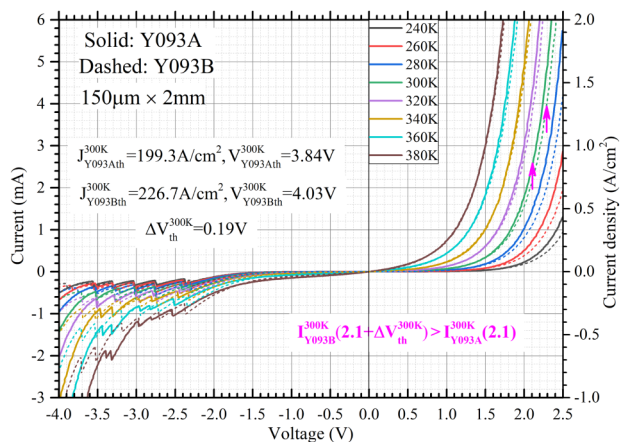


FIG. 12. The DC IV characteristics for two 150 μm -wide ICLs from Y093A and Y093B, respectively. The arrows indicate two corresponding currents for the two devices operated at voltages separated by their threshold voltage difference ΔV_{th} at 300 K.

device from Y093B was higher than Y093A by 0.19 V. Because of the exponential relationship with forward bias voltage V_f , the injection current could increase excessively with a small increase of V_f . Indeed, the current $I_{Y093B}(V_f + \Delta V_{th})$ in Y093B was higher than $I_{Y093A}(V_f)$ in Y093A, as shown in Fig. 12 with an example of $V_f = 2.1$ V indicated by two arrows. Since the carrier density exponentially scales with the inverse of bandgap and the threshold voltage linearly proportional to the bandgap, the injected carrier density can be considered of approximately equal for every device at a normalized voltage $V_n = (V_f + \Delta V_{th})$. Hence, when the current density is higher for a device at this normalized voltage, it is indicative of a shorter carrier recombination lifetime. The decrease in carrier lifetime in Y093B could be caused by increased SRH recombination related to material quality as its surface defect density was higher compared to Y093A. Nevertheless, past studies of type-II ICLs suggested existence of substantial Auger recombination in a wide temperature range from 80 K to above 300 K and its non-monotonic variations with wavelengths.^{24,25} It would require more extensive and thorough investigations to fully understand how different mechanisms affect carrier lifetime and device performance degradation of type-II ICLs with shortening emission wavelength.

C. Narrow ridge ICLs

A piece of wafer Y092 was later processed into 7.5 and 5.5 μm -wide narrow-ridge (NR) devices for cw operation at RT and above. These NR devices were mounted epi-side up without facet coating. A 7.5 $\mu\text{m} \times 2$ mm device lased at temperatures up to 328 K (55 $^{\circ}\text{C}$) with a J_{th} of 1323 A/cm² near 2.99 μm redshifted from 2.87 μm at 280 K as shown in Fig. 13. At 300 K, its cw lasing wavelength was 2.902 μm , very similar to the pulsed lasing wavelength of BA ICLs, but its J_{th} was 475 A/cm², which is more than doubled compared to the BA devices, indicating significant sidewall leakage from this NR device. Consequently, the threshold voltage

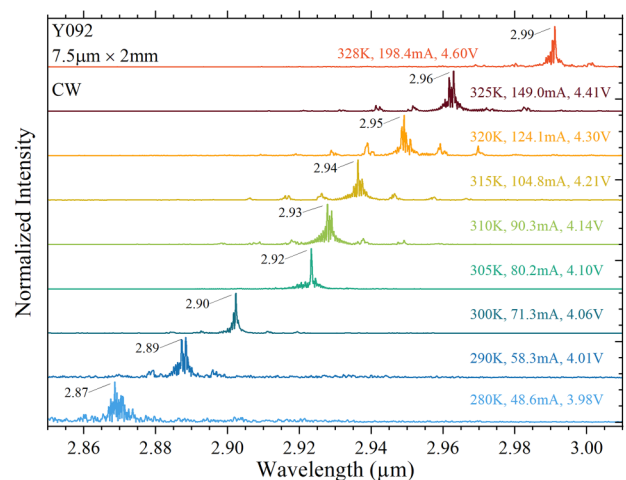


FIG. 13. The cw spectra for a 7.5 $\mu\text{m} \times 2$ mm ICL from Y092.

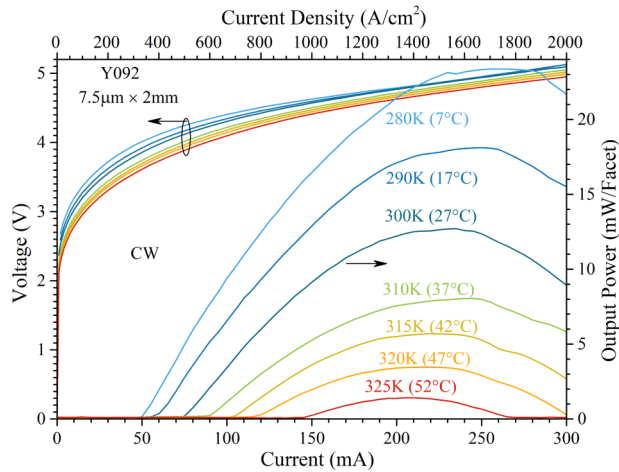


FIG. 14. The cw IVL characteristics for the $7.5\ \mu\text{m} \times 2\ \text{mm}$ ICL from Y092.

(e.g., 4.06 V at 300 K) was higher, corresponding to lower voltage efficiency (63% at 300 K). Nevertheless, this device still delivered substantial output power (e.g., $\sim 13\ \text{mW/facet}$ at 300 K) at RT and above, with operating currents below 250 mA, as shown in Fig. 14. Its slope efficiency at 300 K was $0.136\ \text{W/A/facet}$, corresponding to an EQE of 63.6%. This value of EQE is substantially below the pulsed EQE of 208% for the BA device in Fig. 7, which was mainly again due to significant sidewall leakage. The issue of this sidewall leakage was verified by comparing current density J - V characteristics between the NR device and the BA device as shown in Fig. 15. Although the asymmetric diode rectifying features were maintained, the current density at a given voltage was much higher in the NR device. Additionally, the peak-to-valley current ratios for the NDC features under a reverse bias were reduced substantially in

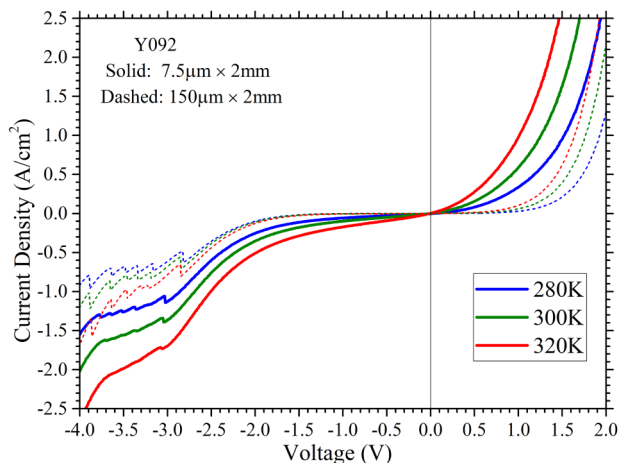


FIG. 15. Comparison of DC JV characteristics for a NR ICL and a BA ICL from Y092.

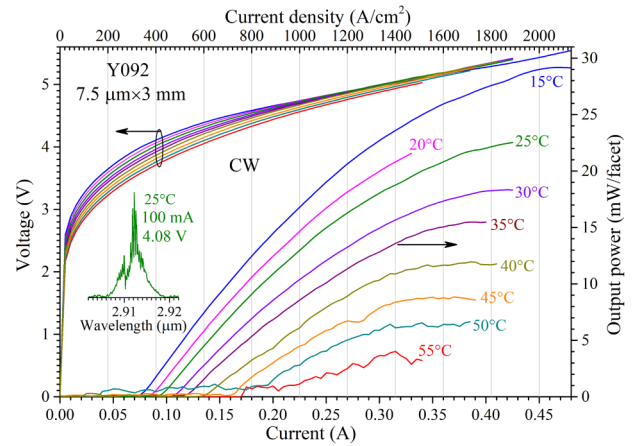


FIG. 16. The cw IVL characteristics for a $7.5\ \mu\text{m} \times 3\ \text{mm}$ ICL on a C-mount. The inset is its cw lasing spectrum at 25°C .

the NR device and the first peak location was shifted to a higher reverse bias due to significant sidewall leakage.

A $7.5\ \mu\text{m} \times 3\ \text{mm}$ device on a standard C-mount lased at temperatures up to 55°C with higher output power and reduced J_{th} due possibly to the lower mirror loss with a longer cavity as shown in Fig. 16. The actual CW operating temperature might be $\sim 5^\circ$ higher than the labeled temperature as the temperature sensor was quite away from the location of the C-mount. This was reflected by the lasing wavelength of $2.912\ \mu\text{m}$ at 25°C , as shown in the inset of Fig. 16, which was longer than the cw lasing wavelength of the $2\ \text{mm}$ -long device at 300 K (Fig. 13). At 25°C , this $3\ \text{mm}$ -long device had a J_{th} of $423\ \text{A/cm}^2$ and an output power exceeding $22\ \text{mW/facet}$ (Fig. 16), which is significantly better than what ($<10\ \text{mW}$ at 25°C) was reported previously for a $3\ \text{mm}$ -long NR Fabry-Pérot SL-cladding ICL at a similar wavelength.²⁶ In addition, the current density at the highest output power point was $\sim 30\%$ higher compared to what for the SL-cladding ICL in Ref. 26. These suggest improved thermal dissipation with the hybrid cladding.

IV. SUMMARY

In summary, RT hybrid-cladding ICLs were demonstrated for emission wavelengths below $3\ \mu\text{m}$, exhibiting threshold current densities and threshold input power densities substantially lower than previously reported values for SL-cladding ICLs at comparable wavelengths. For example, at 300 K, J_{th} was as low as $191\ \text{A/cm}^2$ with a P_{th} of $693\ \text{W/cm}^2$ at an emission wavelength near $2.9\ \mu\text{m}$. NR devices lased in cw mode operation up to 55°C with both threshold current density and output power improved compared to previous SL-cladding ICLs at similar wavelengths. The analysis of these results suggests room for further improvements. Comparative study of devices with different local material qualities from the same wafer and different wafers revealed a certain correlation between SRH recombination and threshold current density, which shed light on why device performance degrades when the lasing

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wavelength of type-II ICLs is shortened. Additionally, NDC features were observed under reverse bias voltage for laser devices, which may provide an interesting and potentially useful diagnostic means to evaluate the material and fabrication qualities of ICLs.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Yixuan Shen: Data curation (lead); Formal analysis (equal); Investigation (lead); Writing – original draft (supporting); Writing – review & editing (equal). **Rui Q. Yang:** Conceptualization (lead); Formal analysis (lead); Funding acquisition (equal); Investigation (equal); Resources (equal); Writing – original draft (lead); Writing – review & editing (lead). **Tetsuya D. Mishima:** Investigation (equal); Validation (equal); Writing – review & editing (supporting). **Michael B. Santos:** Funding acquisition (equal); Investigation (equal); Resources (equal); Validation (equal); Writing – review & editing (equal). **Xiaojun Wang:** Data curation (equal); Investigation (equal); Resources (equal); Validation (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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