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Suppression of carrier leakage in 4.8 µm - emitting quantum cascade lasers

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ABSTRACT

In this work we show that by using both deep quantum wells and tall barriers in the active regions of quantum cascade (QC)-laser structures and by tapering the conduction-band edge of both injector and extractor regions one can significantly reduce the leakage of the injected carriers. Threshold-current, \( J_{th} \) and differential-quantum efficiency, \( \eta_d \) characteristic temperatures, \( T_0 \) and \( T_1 \), values as high as 278 K and 285 K are obtained to 90 °C heatsink temperature, which means that \( J_{th} \) and \( \eta_d \) vary ~ 2.5 slower over the 20-90 °C temperature range than in conventional QC devices. Modified equations for \( J_{th} \) and \( \eta_d \) are derived. In particular, the equation for \( \eta_d \) includes, for the first time, its dependence on heatsink temperature. A model for the thermal excitation of injected carriers from the upper lasing level to upper active-region energy states from where they relax to lower active-region energy states or get scattered to the upper \( \Gamma \) miniband is employed to estimate carrier leakage. Good agreement with experiment is obtained for both conventional QC lasers and deep-well (DW)-QC lasers.

Keywords: Quantum-cascade lasers, mid-infrared, strain-compensated, threshold-current characteristic temperature, slope-efficiency characteristic temperature, carrier leakage.

1. INTRODUCTION

The active medium of conventional quantum-cascade (QC) lasers is composed of a superlattice of quantum wells and barriers of the fixed composition, respectively. As a result, for state-of-the-art devices emitting in the 4.5-5.5 µm range and optimized for high-power CW operation there is substantial carrier leakage from the upper laser level to the continuum, as evidenced by a strong decrease in the differential-quantum efficiency, \( \eta_d \), above 300 K (i.e., the characteristic temperature for \( \eta_d \), \( T_1 \), has a low value of ~ 140 K) and the threshold-current characteristic temperature, \( T_0 \), has values of ~ 140 K above room temperature (RT) (i.e., above 300 K). The low values for both \( T_0 \) and \( T_1 \) are indirectly due to a relatively small energy differential, \( \delta E \), value (i.e., ~ 250 meV) between the upper lasing level and the top of the exit barrier. In turn the maximum RT CW wallplug efficiency (for light emitted from the front facet of devices with high-reflectivity-coated back facets) has values of 11-12 %, far short of theoretically predicted limits (e.g., ~ 28% at \( \lambda \approx 4.6\mu\text{m} \)). A recent study attempted to suppress carrier leakage by incorporating very thin (0.2 nm) AlAs layers into composite barriers used in the 4.8 µm-emitting QC lasers. While the suppression was substantial below 0 °C (\( T_0 \approx 240\text{K} \)), above 0 °C \( T_0 \) improved only modestly (from 143 K to 154 K) while \( T_1 \) remained basically the same (143 K) for conventional QC lasers By using the deep-well concept, we obtained devices with \( \delta E \) values as high as 450 meV. In turn carrier leakage out of the active region is substantially suppressed, which results in devices of much less temperature-sensitive electro-optical characteristics than those of conventional QC devices.

Here we show that by modifying the conventional equations for \( J_{th} \) and \( \eta_d \), to take into account carrier leakage and in the case of \( \eta_d \), backfilling as well, one can obtain reasonably good agreement between calculated and experimentally obtained values for \( T_0 \) and \( T_1 \).

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2. THE DEEP-WELL CONCEPT

We initially grew a strain-compensated InP-based, 5.4 μm QC-laser structure of a published design\textsuperscript{12} from which we obtained\textsuperscript{13} RT lasing results comparable to the best results reported from 5.3 μm devices of same doping level in the injector (i.e., 2x10\textsuperscript{17} cm\textsuperscript{-3}).

Since for MOCVD the optimal growth-temperature range (i.e., 630°C-660°C) is much above the growth temperatures used in gas-source MBE and MBE (i.e., 500-530°C), it has been difficult to grow by MOCVD the highly strained structures required for lasing below 5 μm. Therefore we designed a structure, based on deep quantum wells (QWs) in the active region, to lase at ~ 4.7 μm while growing it at the same temperature (i.e., 630°C) that we used for getting RT lasing at 5.4 μm. Basically only the QWs in the active region are made deep, as necessary for 4.7 μm emission (Fig. 2). For strain compensation, the Al content in the barriers in and around the active region is increased from 56% to 75%, thus providing much taller barriers than in conventional 4.6-4.8 μm QC lasers.\textsuperscript{1-4}

The advantages of the deep-well (DW) 4.8 μm QC structures over conventional 4.8 μm QC structures\textsuperscript{1,2} can be summarized as such: 1) Much more flexibility in design as highly-strained layers are limited only to the active region; 2) Much less carrier leakage from the active QWs since the barrier layers, in and around the active region, are taller (e.g., the energy difference between the exit-barrier top and the upper lasing state is ~ 200 meV larger than in conventional devices). In turn that leads to much less temperature sensitivity of the lasers’ electro-optical characteristics. Furthermore, active regions with suppressed carrier leakage are quite relevant for the development of highly efficient intersubband quantum box (IQB) lasers\textsuperscript{14} since the longer the upper-laser-level lifetime, the more sensitive the devices are to carrier leakage to the continuum. Thus the development of DW-QC devices has been pursued not only for improving the performance and reliability of QC lasers, but also as a means to fulfill the promise that IQB devices hold of achieving continuous-wave (CW) wallplug efficiencies as high as 50 % at room temperature\textsuperscript{15}.

![Fig. 2. Conduction-band diagram and relevant wavefunctions for deep-well 4.7 μm QC laser](image-url)
3. DEVICE STRUCTURES AND RESULTS

We show in Fig. 3, for comparison, the band diagrams and relevant wavefunctions for conventional QC lasers and optimized DW-QC lasers with the double-phonon resonance (DPR) design for depopulation of the lower laser level.

(a)

(b)

Fig. 3. Conduction-band profile and key wave functions for: a) Conventional QC laser (Ref. 2) emitting at 4.6 μm. b) Deep-well QC laser (Ref. 10) under an electric field of 76 kV/cm (λ = 4.8 μm). The upper lasing level is labeled as 4, while 5 and 6 are upper energy states in the active region. The band profile at the top of each figure corresponds to the X valley.
First of all, increasing the barriers’ height increases the energy difference between the upper lasing level (state 4) and the next highest active-region (AR) energy state (state 5) from 46 meV to 60 meV. As we shall see below, this significantly reduces carrier leakage due to thermal excitation to state 5 and subsequent relaxation to the lower AR energy states 3, 2 and 1.

The second major difference is that the energy difference between state 6 and the bottom state of the upper \( \Gamma \) miniband (in the extractor region) increases from 70 meV to 150 meV. This large increase is mostly due to the fact that tapering of the injection region causes the lowest state of the upper miniband (not shown in Fig. 3b) to be “drawn away” from the extractor region. In turn carrier leakage to continuum via electron thermal excitation from state 6 to the lowest two states of the upper \( \Gamma \) miniband is completely suppressed.

Fig. 4 shows the electro-optical characteristics for the DW-QC lasers of conduction-band diagram shown in Fig. 3b. The details of the laser structure are provided in Ref. 10.

![Fig. 4](image_url)  
Left side: Pulsed L-I curves as the heatsink temperature, \( T \), varies. Inset: spectrum; Right side: \( J_{th} \) and the slope efficiency, \( \eta_s \), as a function of \( T \). \( T_0 \) and \( T_1 \) are characteristic temperatures for \( J_{th} \) and \( \eta_s \). Inset: \( J_{th} \) vs. \( T \) from 80 K to 333 K.

Ridge-guide devices were mounted epi-side up on Cu blocks and measured in pulsed mode (100 ns, 2 kHz). The threshold-current density, \( J_{th} \), at 20 °C is 1.78 kA/cm². The voltage at threshold is 11.2 V at 20 °C which is comparable to those for conventional devices. The characteristic temperature for \( J_{th} \), as defined by:  

\[ J_{th}(T_{in} + \Delta T) = J_{th}(T_{in}) \exp(\Delta T/T_0), \]

where \( T_{in} + \Delta T \) is the heatsink temperature, \( T \), and \( T_{in} \) is the initial \( T \), is 260 K for 20-60 °C, and 243K for 60-90 °C. The inset in the right side of Fig. 4 shows that \( T_0 \approx 315 \) K for the 80-293 K temperature range. For another device, which has a somewhat higher \( J_{th} \) (i.e., 1.87 kA/cm² at 20 °C) \( T_0 = 278 \) K over the entire 20-90 °C temperature range. By comparison, \( T_0 \) is only 143 K for high-performance conventional 4.6 µm QC lasers over the same temperature range. Similarly, for both devices the characteristic temperature for slope efficiency, \( \eta_s \), defined by:  

\[ \eta_s(T_{in} + \Delta T) = \eta_s(T_{in}) \exp(-\Delta T/T_1), \]

is 285 K over 20-90 °C (right side of Fig. 4) as compared to only \( \sim 140 \) K for 4.6-4.8 µm QC lasers operating over the 20-60 °C [Ref. 1] and 0-50 °C [Ref. 6] temperature ranges.

The high \( T_0 \) values (260-278 K), together with a high \( T_1 \) value of 285 K not only indicate a strong suppression of carrier leakage, but also provide indirect proof that leakage to the indirect valleys (X or L) is not an issue, in the 4.5-5.0 µm range, when heavily-strained (= 1%) \( \text{In}_{0.66}\text{Ga}_{0.34}\text{As} \) QWs are used. Furthermore, the high \( T_0 \) and \( T_1 \) values should significantly improve CW operation. On the one hand \( T_0 \) is directly related to the maximum temperature for CW lasing, \( T_{\text{max}} \), and the maximum CW power at a given heatsink temperature, \( P_{\text{max}} \). On the other hand, since both \( P_{\text{max}} \) and the maximum wallplug efficiency, \( \eta_{w_{\text{p, max}}} \), are proportional to \( \eta_s \), both quantities depend strongly on \( T_1 \). Thus high \( T_0 \) should result in increased \( T_{\text{max}} \), while high \( T_0 \) and \( T_1 \) should provide significantly higher \( P_{\text{max}} \) and \( \eta_{w_{\text{p, max}}} \). For example, we estimate that RT CW wallplug efficiency values in excess of 20% at 4.8 µm (front facet only) become possible.
4. MODIFIED EQUATIONS FOR THE THRESHOLD CURRENT AND THE DIFFERENTIAL QUANTUM EFFICIENCY

The conventional equations\textsuperscript{11} for $J_{th}$ and the differential quantum efficiency, $\eta_d$, need to be modified to include the effect of carrier leakage and in the case of $\eta_d$ of the backfilling as well\textsuperscript{14}. It is assumed that the efficiency of tunneling injection from the injector to the upper lasing state, $\eta_{inj}$, is unity. $J_{th}$ is the sum of the threshold-current density in the absence of backfilling and carrier leakage, $J_{0,th}$, the current density due to backfilling, $J_{bf}$, and the current density due to carrier leakage, $J_{leak}$, each of which are defined below:

$$J_{0,th} = \frac{q}{\tau_{up}} \alpha_{tot,nonres} g_c N_p$$

$$J_{bf} = \frac{q}{\tau_{up}} n_s \exp(-\Delta_{inj}/kT)$$

$$J_{leak} = \frac{q}{\tau_{leak}} n_5 + \frac{q}{\tau_{6,leak}} n_6$$

where $\tau_{up}$ is the “effective” upper state lifetime\textsuperscript{7}, $\alpha_{tot,nonres}$ is sum of the mirror loss, $\alpha_m$, and non-resonant waveguide losses\textsuperscript{17}, $g_c$ is the modal gain cross section per period\textsuperscript{5}, $N_p$ is number of periods, $n_s$ is the electron sheet density in the injector, $\Delta_{inj}$ is the energy difference between the lower laser level and the ground state in the next injector\textsuperscript{17}, $T$ is the heatsink temperature, $n_5$ and $n_6$ are the electron sheet densities in the active-region upper states 5 and 6, $\tau_{5,leak}$ and $\tau_{6,leak}$ are the lifetimes corresponding carrier leakage in states 5 and 6, respectively. More specifically $\tau_{5,leak} = (1/\tau_{53} + 1/\tau_{52} + 1/\tau_{51})\textsuperscript{-1}$ and $\tau_{6,leak} = (1/\tau_{65} + 1/\tau_{63} + 1/\tau_{62} + 1/\tau_{61})\textsuperscript{-1}$, where $\tau_{6,um}$ is the lifetime corresponding to the electrons being scattered from state 6 to states in the upper $\Gamma$ miniband and the other lifetimes correspond to electron relaxation from states 5 and 6 to states 1, 2, and 3, respectively. $n_5$ and $n_6$ are obtained from the following equations:

$$n_5 = n_4 \frac{\tau_{5,tot}}{\tau_{45}} + n_6 \frac{\tau_{5,tot}}{\tau_{65}}$$

$$n_6 = n_5 \frac{\tau_{6,tot}}{\tau_{56}}$$

where $\tau_{5,tot}$ and $\tau_{6,tot}$ are the lifetimes corresponding to electron scattering from state 5 to states 1, 2, 3, 4 and 6 and from state 6 to states 1, 2, 3, 4, 5 and states in the upper $\Gamma$ miniband, respectively, and $n_4$ is the electron sheet density in state 4.

The lifetime corresponding to thermal excitation of electrons from state $i$ to state $j$, $\tau_{ij}$, which is predominantly due to LO-phonon absorption scattering for large energy separations, is approximated from the following expression:

$$\frac{1}{\tau_{ij}} = \frac{1}{\tau_{ji}} \exp\left(-\frac{E_{ji} - \hbar \omega_{LO}}{kT_{ei}}\right) \left(1 - \exp\left(\frac{\hbar \omega_{LO}}{kT}\right)\right)$$

where $E_{ji}$ is the energy difference between states $j$ and $i$, $\hbar \omega_{LO}$ is the phonon energy, and the rightmost term corresponds to the occupation number of phonons (assumed to be in thermal equilibrium with the lattice). $T_{ei}$ is the electronic temperature in state $i$, which under very low duty-cycle operation (i.e., negligible Joule heating) is obtained from: $T_{ei} - T = \alpha_{e,L} \cdot J$, where $T$ is the heatsink temperature and $\alpha_{e,L}$ is the electron-lattice coupling constant\textsuperscript{18}.

For the (external) differential quantum efficiency, $\eta_d$, it has been shown\textsuperscript{14} that, by imposing the condition that the population inversion remains unchanged above threshold, one obtains: $\eta_d = \eta_{inj} \frac{J_{0,th} J_{bf}}{J_{0,th} J_{bf}} \alpha_m \left(\alpha_{tot,nonres}\right) N_p$, where $\alpha_m$ is the mirrors loss, $\eta_{inj}$ is the differential efficiency of the laser transition\textsuperscript{7} and $J_{0,th}$ includes the backfilling current density, $J_{bf}$.

We modify that equation by including the leakage current density, $J_{leak}$, and defining a pumping efficiency term, $\eta_p$:
\[ \eta_p = \frac{J_{0,th}}{J_{0,th} + J_{bf} + J_{leak}} \]  

(7)

and then the equation for \( \eta_d \) becomes:

\[ \eta_d = \eta_p \eta_{tr} \frac{\alpha_m}{\alpha_{tot,nonres}} N_p \]  

(8)

The product of \( \eta_p \) and \( \eta_{tr} \) is in effect the laser internal efficiency, \( \eta_i \). Since \( \eta_{tr} \) is virtually temperature independent, and assuming that the non-resonant waveguide losses vary negligibly with temperature for wavelengths in the 4.5-5.5 \( \mu \)m range, it follows that the temperature dependence of \( \eta_d \) (and hence that of the slope efficiency) is determined by the temperature dependence of backfilling and carrier leakage. This fact in turn explains to a large extent the experimentally observed drop in \( \eta_d \) with increasing temperature, especially above 300 K (i.e., the \( T_1 \) parameter). We also note that, at a given heatsink temperature, changing the mirrors loss by changing the cavity length, \( L \), or the reflectivity of the front facet, \( R_f \), will change the value of the device internal efficiency. That is, \( \eta_i \) is a function of \( L \) and \( R_f \), which in turn means that deriving values for \( \eta_i \) and \( \alpha_{w,nonres} \) from 1/\( \eta_d \) vs. \( L \) plots or 1/\( \eta_d \) vs. 1/\( \alpha_m \) plots, when \( L \) or \( R_f \) are varied over relatively wide ranges, may not be provide correct results.

5. ESTIMATE OF THE TEMPERATURE DEPENDENCE OF THE THRESHOLD CURRENT AND THE DIFFERENTIAL QUANTUM EFFICIENCY

By using the above equations we estimated the temperature variation of \( J_{th} \) and \( \eta_d \) over the temperature range 300 K to 360 K. The structures used are of the conventional type (Fig. 3a) and deep-well type (Fig. 3b) considering 3 mm-long devices with uncoated facets. Since lifetimes due to inelastic and elastic scattering are of similar value in the 4.0-5.0 \( \mu \)m range\(^{21} \) we halved the lifetimes obtained from a \( kp \) code considering only inelastic scattering and since the elastic-scattering lifetimes are basically temperature independent\(^{21} \) we assumed that the lifetimes vary half as fast with temperature than when only inelastic scattering is considered (i.e., LO-phonon assisted scattering). Furthermore, the presence of elastic scattering (due to interface roughness) causes the electroluminescence linewidth, \( 2\gamma_{el} \), to vary much less than if LO-phonon scattering is considered\(^{22} \). That is, over the 300-360 K temperature range, the characteristic temperature coefficient for the \( 2\gamma_{el} \) parameter (as it increases) is \( \sim 410 \) K if only LO-phonon scattering is considered as opposed to \( \sim 700 \) K as observed from experiment\(^{22} \). Since in the \( J_{0,th} \) equation the main terms that vary with temperature are the upper-state lifetime, \( \tau_4 \), and \( 2\gamma_{el} \) we find that its \( T_0 \) value increases from 250 K when only LO-phonon scattering is considered to 450 K when both inelastic and elastic scattering are considered.

We use the backfilling current as a fitting parameter with \( \Delta \) values of 100 meV for conventional devices and 120 meV for deep-well devices. The former value is consistent with values smaller than the designed ones, which are obtained from the V-I characteristics of conventional devices\(^{17,23} \). The reason for this discrepancy is unknown. For calculating \( T_{ei} \) we use an \( \alpha_{el-ei} \) value of 35 K cm\(^2\)/kA as measured\(^{24} \) for the electronic temperature of the injector ground state, \( T_{eg} \), of 4.8 \( \mu \)m-emitting, strain-compensated QC lasers. Since state \( g \) is strongly coupled to the upper laser level, we feel comfortable to assume that, at threshold, \( T_{e4} \approx T_{eg} \). We also assume that \( T_{e5} \approx T_{e6} \approx T_{e4} \), although \( T_{e5} \) and \( T_{e6} \) may have different values than \( T_{e4} \).

Table 1. Estimated parameters for conventional and deep-well QC lasers of the DPR design (\( \lambda = 4.6-4.8 \) \( \mu \)m).

<table>
<thead>
<tr>
<th>Item</th>
<th>Laser type</th>
<th>Measured ( T_0 ) (300-360 K)</th>
<th>( J_{leak} / J_{th} )</th>
<th>Estimated Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.144</td>
<td>Conventional QC</td>
<td>143 K</td>
<td>0.144</td>
<td>0.210</td>
</tr>
<tr>
<td>0.087</td>
<td>Deep-Well QC</td>
<td>260-278 K</td>
<td>0.087</td>
<td>0.128</td>
</tr>
</tbody>
</table>

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Table 1 shows calculated values for the \( J_{\text{leak}}/J_{\text{th}} \) ratio at 300 K and 360 K heatsink temperature, \( T \), and \( T_0 \) and \( T_1 \), the characteristic temperature for \( J_0 \) and \( \eta_0 \), respectively, for conventional QC lasers and DW-type QC lasers of the DPR design (for depopulating the lower laser level), 30 stages and emitting in the 4.6-4.8 \( \mu \)m wavelength range. For conventional QC lasers the value of \( J_0 \) at 300 K is taken to be 1.9 kA/cm\(^2\), as deduced from experimental data by considering uncoated, 3 mm-long chips. For DW-QC lasers \( J_0 \) at 300 K is the one experimentally obtained from uncoated, 3 mm-long chips: 1.87 kA/cm\(^2\) (Fig. 4 in Ref. 10). For both device types, the ratio of the values for the quantity \( J_{0,\text{leak}}/J_{\text{bf}} \) at 360 K and at 300 K is used as a scaling factor when calculating \( J_{\text{leak}} \) at 360 K.

The primary carrier-leakage path is found to be relaxation from state 5 to the lower AR states 3, 2 and 1 of carriers thermally excited from the upper lasing level, state 4, to state 5. The secondary leakage path, which matters only for conventional QC lasers, is thermal excitation from state 6 to the upper-\( \Gamma \)-miniband levels, and subsequently to the continuum, of carriers thermally excited from state 4 to state 5 and then to state 6.

The main reason why the relative carrier leakage (i.e., \( J_{\text{leak}}/J_0 \)) is significantly larger for conventional devices that for DW devices is that the \( E_{54} \) value is 46 meV in the former compared to 60 meV in the latter. The higher \( E_{54} \) value for DW devices is a consequence of much taller barriers than in conventional devices. A higher \( E_{54} \) value impacts \( J_{\text{leak}} \) mostly through the value of the scattering time \( \tau_{45} \). For example, at 360 K \( \tau_{45} \) has values of 0.32 ps and 0.84 ps for conventional and DW devices, respectively. The difference is due to both the \( E_{54} \) value in the thermal-activation term of Eqn. 6 as well as to the difference in \( \tau_{45} \) values (i.e., 0.12 ps vs. 0.21 ps) which in turn is a consequence of how much larger the \( E_{54} \) value is compared to the phonon energy (i.e., a measure of how non-resonant the phonon-assisted scattering is).

Leakage from state 6 to the continuum is basically inexistent in DW devices because of the large energy difference between state 6 and the bottom of the upper-\( \Gamma \)-miniband, \( E_{6,\text{um}} \) (i.e., 150 meV, as seen from Fig. 3 b) which in turn gives \( \tau_{6,\text{um}} \) values of the order of 500 ps at 300 K and 200 ps at 360 K. In sharp contrast, for conventional devices \( E_{6,\text{um}} \) has a value of 70 meV (Fig. 3a) which coupled with significant overlap between the wavefunction of state 6 and the wavefunctions of the lower states of the upper miniband gives much smaller \( \tau_{6,\text{um}} \) values: 2.4 ps at 300 K and 1.3 ps at 360 K. Notwithstanding, leakage through the upper miniband at such 360 K is found to account for only 10 % of \( J_{\text{leak}} \) due to the relatively high value of \( E_{65} \) (i.e., 80 meV). The carrier leakage to the continuum may actually be higher if the electronic temperatures of states 5 and 6 are higher than that of the upper laser level, state 4, which in turn will lower the estimated values for \( T_0 \) and may require adjusting the value of \( \Delta_{\text{inj}} \) to get good fit with experiment. Hence, further detailed numerical calculations are needed to estimate the carrier leakage more accurately. Another parameter that may affect the \( T_0 \) and \( T_1 \) values is the temperature dependence of the non-resonant intersubband absorption portion of the waveguide loss.
lasers vary with temperature about 2.5 times slower than those parameters for conventional, high-performance QC lasers. This dramatic suppression of carrier leakage indicates that we are approaching temperature dependences determined mainly by inelastic and elastic scattering and backfilling. The virtual doubling of $T_0$ and $T_1$ above room temperature should lead to significantly improved CW performance as well as greater long-term reliability at watt-range CW powers. Furthermore, the demonstration of the suppression of carrier leakage makes the stage(s) of DW-QC devices ideally suited for incorporation in IQB-laser structures.

In addition the conventional equations for the threshold current and the external differential quantum efficiency, $\eta_d$, have been modified to reflect carrier leakage and in the case of $\eta_d$ backfilling as well. Thus a temperature dependence is introduced for $\eta_d$ which, for the first time, can account for the commonly observed decreases in $\eta_d$ above room temperature. Carrier leakage paths are identified, and estimated values for $T_0$ and $T_1$ are found to be in good agreement with experimental values for both conventional QC lasers and deep-well QC lasers.

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