Ultrahigh Gain from Plasmonic Quantum Dot Nanolaser

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Abstract. This work studies the gain from quantum dot plasmonic nanolaser. A metal/semiconductor/metal structure was considered to attain plasmonic nanocavity with active region contains: quantum dot, wetting layer and barrier layers. Band alignment between layers was used to predict their parameters. Momentum matrix element for transverse magnetic mode in quantum dot structure was formulated. Waveguide Fermi energy was introduced and formulated, for the first time, in this work to cover the waveguide contribution (Ag metal layer) in addition to the active region. The gain obtained here overcomes the electron scattering losses which promises in high gain, high power and high speed applications. The waveguide Fermi energy goes deep in the valence band which explains the high gain, where it is shown that covering the structure by a metal makes valence band quantum dot states fully occupied which refers to an efficient hole contribution.

Keywords: Plasmonic, Quantum dot, Nanolaser.

1. Introduction

After the foundation of nanotechnology, the concept of nanolaser was developed in 2003 [1] where the laser waveguide (not only the active region) becomes in nanoscale dimensions. When the size of the laser becomes in nanoscale, both gain and cavity modes are treated quantum mechanically. This is the main difference between nanolaser, and conventional semiconductor lasers. There are several kinds of nanolaser have been explored in recent years including: nano-pillar, nano-wires, spaser-based, nano-patch, and nano-rod lasers [2].

If electromagnetic (EM) waves are propagate in a metallic medium then we have surface plasmons (SPs). They are the quanta of the interaction between electron oscillations in metal with photons. SPs are depend on the plasma frequency of the metal [3]. In another case, when EM waves propagate in a dielectric medium we have surface polaritons. Plasmonic nanolaser confines light at a sub-wavelength scale by storing light energy in electron oscillations which is the “surface-plasmon-polaritons (SPPs)” [4-8]. Plasmonic waveguide nanocavity that supports SPPs was based on metal-semiconductor-metal (MSM) waveguide of finite length where the semiconductor is the active region, see figure 1. SPPs are
EM waves propagate along a metal-dielectric interface. SPPs are the quanta of the interaction of metal plasmons with photons in dielectric [9].

One of the main concerns behind reducing the laser cavity and waveguide core size is the reduction of threshold and low power consumption. It is infeasible with dielectric cladding due to the mirror loss limitations. The main obstacle to shrink the cavity size is the diffraction limit \((\lambda/n_{\text{eff}})^3\) where \(n_{\text{eff}}\) is the effective cavity refractive index and \(\lambda\) is the cavity mode resonant wavelength [8].

The diffraction limit puts the lower bound on transverse size of the mode in the dielectric waveguide. A considerable part of the mode profile spreads out into the dielectric cladding which increases the scattering loss and then reduces gain [9]. Metal cladding can reduce the field penetration which reduces the leakage from the radiative power, and then becomes efficient in confining the mode in a very small size below the diffraction limit due to its negative real part of permittivity at optical frequencies [10, 12]. In this case, the surface plasmons in metals coupled with the optical modes are contributed in the SPPs which are less restricted by the diffraction limit. Thus, placing a dielectric between two metallic claddings assures the bounding of the effective mode volume by metal than spreading outside the dielectric since the decay of the optical field into the metal side is faster than that in the dielectric side [13]. But the main challenge, thereafter, is the significant material loss of metal, which requires high gain active medium to balance metal and mirror losses [11].

Due to their quantized energy states similar to natural atoms or molecules, quantum dots (QDs) are particularly attractive. Thus, QDs can be regarded as zero-dimensional structures where their electronic motion is confined in all the three spatial dimensions. They exhibit unexpected characteristics due to their incredibly small size with quantum mechanical behavior [14]. QD structure contains a QD layer grown on a wetting layer (WL), which is in the form of a quantum well (QW) layer. These two layers (QD and WL) are then covered by the barrier (B) that is in the form of bulk layer. QD active region can be introduced into a nanolaser as a high gain layer.

This work estimates the gain from QD nanolaser where its structure was MSM plasmonic nanocavity with QD semiconductor active region. Li and Nang shows a high net modal gain in plasmonic nanolaser (with bulk active region) and assign it to the slowdown in the average energy that propagates in the structure. They assign high optical confinement factor as the reason of increment the net modal gain which is the only measurable quantity [15, 16]. Both optical confinement factor and material gain cannot be measured [2]. Our recent work searches this point. While it is possible to consider QD layer only, considering both WL and B is so important to obtain calculations that simulates the real practical structures [14, 17-20]. Band alignment between layers [21] was used to predict their parameters. Momentum matrix element for transverse magnetic (TM) mode in the QD structure was formulated. It is found here, that the addition of metal rearranges the chart of the structure substantially. The Fermi energy of the active region was rearranged also. This is with the many works about metal-semiconductor contacts [22, 23]. Fermi energy in earlier works consider the active region contribution only (QD-WL-B) as in [17, 18]. Here, contribution of metal waveguide was considered (and formulated) to calculation the Fermi energy of QD nanolaser. Our recent Fermi
energy takes QD-WL-B-M (with M refers to metal), i.e. it is a “waveguide Fermi energy, WFE”. It is introduced here for the first time to explain results of high gain. This predicts result with that of Li and Nang [15, 16]. It is shown that covering the structure by a metal (Ag) increases the material gain by a hug value compared with that obtained from conventional QD laser.

2. Quasi-Fermi Distribution Function

Fermi-Dirac distributions are described by Fermi function \( f_c(E', F_c) \) for electrons in the conduction band (CB), and \( f_v(E', F_v) \) for holes in valence band (VB) which are expressed as [24],

\[
f_c(E', F_c) = \frac{1}{1 + \exp\left[\left(\frac{E_g + \frac{m_e^*}{m^*} (E' - E_c^{th}) - F_c}{k_B T}\right)\right]} \tag{1}
\]

\[
f_v(E', F_v) = \frac{1}{1 + \exp\left[\left(\frac{m_{hh}^*}{m_{hh}^*} (E' - E_v^{th}) - F_v}{k_B T}\right)\right]} \tag{2}
\]

Where \( E' \) is the optical transition energy, \( F_c \) and \( F_v \) are the quasi-Fermi levels (QFLs) of CB and VB, respectively. \( E_g \) is the bandgap energy of the self-assembled QD. \( E_{eq} \) and \( E_{hi} \) represents the discrete confined energy of the QD states in CB and VB. The term \( E_{eq}^{th} = E_g + E_{el} - E_{hi} \) represents the optical transition energy due to the optical recombination between the \( i \)th QD electron and heavy hole states. \( m_e^* \) and \( m_{hh}^* \) are the effective masses of the electron and heavy hole in QDs, respectively. The reduced effective mass is obtained from the relation \( 1/m_e^* = 1/m_e^* + 1/m_{hh}^* \).

3. Metal/Semiconductor Contact

The nanolaser structure under study is formed from a noble metal Ag-layer, semiconductor, and substrate. This is what is called MSM. The semiconductor layer (gain layer) of MSM plasmonic nanocavity is composed from GaAs (B), InGaAs (WL) and InAs (QD) as an active region. In this semiconductor structure (B-WL-QD), the barrier was in the form of bulk semiconductor layer. Both cladding and substrate are Ag-metal layer, see Fig.1.

Figure 2 depicts MSM band alignment, where the work function of metal before contact is higher than that of semiconductor \( (Q_m > Q_s) \). As a result, the Fermi energy level of the semiconductor \( (E_{Fs}) \) becomes higher than that of the metal \( (E_{Fs} > E_{Fm}) \). After contact, the work function of the metal becomes equal to that of the semiconductor \( (Q_m = Q_s) \) and as a result, their Fermi energies becomes equal \( (E_{Fs} = E_{Fm}) \) [25]. Note that, \( E_c \) represents CB edge, while \( E_v \) is the VB edge.

![Figure 2](image-url)

**Figure 2.** Metal/semiconductor band alignment in two cases: (a) before, (b) after contact.
Figure 3 shows the energy band diagram of the QD nanolaser used in this work. The band-edge of GaAs which is a metal/barrier (M/B) was calculated in CB as: 

$$\Delta E_{c}^{(M/B)} = E_{c}^{M} - E_{c}^{B}$$

taking with $$\Phi^{M}$$ is the work function of metal. 

$$\Delta E_{c}^{(Q/D)} = E_{c}^{B} - E_{c}^{Q/D} = Q_{c} \Delta E_{g}$$

with $$\Delta E_{g} = E_{g}^{B} - E_{g}^{Q/D}$$. The band-edge of M/B in the VB can be calculated by the same way using $$Q_{v} = 1 - Q_{c}$$. Since both $$E_{c}^{B}$$ and $$E_{c}^{Q/D}$$ are obtained, then $$\Delta E_{c}^{(M/B)}$$ can be obtained. Note that $$Q_{c}$$ and $$Q_{v}$$ are the partition ratios of the band edge discontinuities.

![Figure 3. Energy band diagram of the plasmonic QD nanolaser structure.](image)

Since the optical gain of the plasmonic QD nanolaser was investigated, here, at room temperature, thus, the carrier distribution can be assumed to be in quasi-equilibrium. For the QD nanolaser under study: InAs (QD)/InGaAs (QW)/GaAs (B)/Ag (M) layers, we can determine QFLs of the CB ($$E_{c}$$) and VB ($$E_{v}$$) numerically from the surface carrier density per QD layer as follows,

$$n_{2D} = N_{D} \sum_{l} \frac{s_{l}}{2\pi a_{2}} \int \frac{1}{1+e^{(E_{c}^{M} - E_{c}^{B})/k_{B}T}} dE_{c}^{l} +$$

$$\sum_{l} \frac{m_{e}^{*}k_{B}T}{\pi \hbar} \ln \left(1 + e^{(E_{c}^{Q/D} - E_{c}^{B})/k_{B}T}\right) + t_{B} \int \frac{1}{2\pi L_{B}^{2}} \frac{1}{\sqrt{2\pi \sigma_{2}}} \frac{1}{1+e^{(E_{c}^{M} - E_{c}^{B})/k_{B}T}} dE_{c}^{l} +$$

$$t_{M} \int \frac{1}{2\pi L_{M}^{2}} \frac{1}{\sqrt{2\pi \sigma_{2}}} \frac{1}{1+e^{(E_{c}^{M} - E_{c}^{B})/k_{B}T}} dE_{c}^{l}$$

$$\sum_{m} \frac{m_{e}^{*}k_{B}T}{\pi \hbar} \ln \left(1 + e^{(E_{v}^{Q/D} - E_{v}^{B})/k_{B}T}\right)$$

$$+ t_{B} \int \frac{1}{2\pi L_{B}^{2}} \frac{1}{\sqrt{2\pi \sigma_{2}}} \frac{1}{1+e^{(E_{v}^{M} - E_{v}^{B})/k_{B}T}} dE_{v}^{l} +$$

$$t_{M} \int \frac{1}{2\pi L_{M}^{2}} \frac{1}{\sqrt{2\pi \sigma_{2}}} \frac{1}{1+e^{(E_{v}^{M} - E_{v}^{B})/k_{B}T}} dE_{v}^{l}$$

$$n_{2D} = n_{2D} = N_{D} \sum_{l} \frac{s_{l}}{2\pi a_{2}} \int \frac{1}{1+e^{(E_{c}^{M} - E_{c}^{B})/k_{B}T}} dE_{c}^{l} +$$

$$\sum_{l} \frac{m_{e}^{*}k_{B}T}{\pi \hbar} \ln \left(1 + e^{(E_{c}^{Q/D} - E_{c}^{B})/k_{B}T}\right) + t_{B} \int \frac{1}{2\pi L_{B}^{2}} \frac{1}{\sqrt{2\pi \sigma_{2}}} \frac{1}{1+e^{(E_{c}^{M} - E_{c}^{B})/k_{B}T}} dE_{c}^{l} +$$

$$t_{M} \int \frac{1}{2\pi L_{M}^{2}} \frac{1}{\sqrt{2\pi \sigma_{2}}} \frac{1}{1+e^{(E_{c}^{M} - E_{c}^{B})/k_{B}T}} dE_{c}^{l}$$

$$\sum_{m} \frac{m_{e}^{*}k_{B}T}{\pi \hbar} \ln \left(1 + e^{(E_{v}^{Q/D} - E_{v}^{B})/k_{B}T}\right)$$

$$+ t_{B} \int \frac{1}{2\pi L_{B}^{2}} \frac{1}{\sqrt{2\pi \sigma_{2}}} \frac{1}{1+e^{(E_{v}^{M} - E_{v}^{B})/k_{B}T}} dE_{v}^{l} +$$

$$t_{M} \int \frac{1}{2\pi L_{M}^{2}} \frac{1}{\sqrt{2\pi \sigma_{2}}} \frac{1}{1+e^{(E_{v}^{M} - E_{v}^{B})/k_{B}T}} dE_{v}^{l}$$

(3)

(4)
Where \( n_{2D} \) and \( p_{2D} \) are the surface densities of the electrons and holes per QD layer, respectively. \( E^0_\text{e} \) and \( \sigma_\text{e} \) are the \( i \)th maximum and the spectral variance of the QD electron distribution, respectively. In the same manner, \( E^0_\text{h} \) and \( \sigma_\text{h} \) are the \( j \)th maximum and the spectral variance of the QD heavy-hole distribution. The term \( E^0_\text{c} \) is the energy in the CB and \( E^0_\text{h} \) is the energy in the VB. \( m^w_\text{e}(m^w_\text{h}) \) is the effective electron (hole) mass, while \( E^w_\text{e} \) \( (E^w_\text{h}) \) is the subband edge of the CB (VB) of the InGaAs-QW WL. \( t_\text{b} \) is the thickness of the GaAs barrier layer. \( m^b_\text{e}(m^b_\text{h}) \) and \( E^b_\text{e} \) \( (E^b_\text{h}) \) are the carrier mass and the band edge of the CB (VB) of the GaAs barrier layer, respectively. \( t_\text{m} \) is the thickness of the Ag metal layer. \( m^M_\text{e}(m^M_\text{h}) \) and \( E^M_\text{e} \) \( (E^M_\text{h}) \) are the carrier mass and the band edge of the CB (VB) of the Ag layer. In this work, relations (3) and (4) are covering the metal contributions to QD gain. Relations of conventional QD laser that covers B, WL, and QD contributions, only, are discussed in [18, 21]. Eqs. (3) and (4) are one of the main contributions of this work. We recall \( F_\text{c} \) and \( F_\text{v} \) results from Eqs. (3) and (4) as waveguide Fermi energies since it includes the contribution of the metal covers the waveguide structure.

4. Material Gain of Plasmonic QD Nanolaser

In this work, the material gain is calculated for QD plasmonic nanolaser at room temperature. Suppose that the structure was a multilayer QD structure with Ag metal covers both sides of the structure, as in figure 4 QDs are assumed in the form of quantum disks. Using a disk radius of \( a=14 \) nm and a height of \( h=2 \) nm, energy subbands in the QD (InAs) and WL (InGaAs) are calculated using the quantum disk mode [18]. This model was checked with experiment [14, 19].

The light hole states are neglected from the gain calculations because they are deeper than those of heavy hole (hh) [25]. The optical transitions occur between electron-heavy hole states (e-hh) as: \( (e1-hh1), (e2-hh2), \) and \( (e3-hh3) \), where the transition are assumed between CB and VB states of the same quantum numbers of subbands, the effect of all the subbands on each subband are considered – thereafter- in the inhomogeneity. where the subscript \( (i=1, 2, 3) \), refers to the \( i \)th conduction electron-heavy hole transitions. The material gain is calculated from the relation [17],

\[
g(h\omega) = \frac{\pi e^2}{n_\text{b} c \varepsilon_0 m^w_\text{e} \omega} \sum_i \int_{-\infty}^{+\infty} dE' |M_{\text{env}}|^2 \left| \hat{e} \cdot p \right|^2 \times D(E')L_g(E', h\omega) [f_\text{c}(E', F_\text{c}) - f_\text{v}(E', F_\text{v})] \tag{5}
\]

Figure 4. Active region of plasmonic QD nanolaser structure.
Where the $i$th summation runs over all the radiative transitions. $\omega$ is the optical angular frequency, $n_b$ is the background refractive index of the material, $c$ is the speed of light in free space, $\varepsilon_r$ is the permittivity of free space, $m_e$ is the free electron mass, and $E'$ is the optical transition energy. Note that $|M_{env}|$ is the envelope function overlap between the QD electron and hole states. It is assumed that the envelope function overlap is nearly one between the QD electron and hole states of the same quantum numbers [17]. The density of states of self-assembled QDs $D(E')$ covers the inhomogeneous broadening of QDs. When the spectral variance of QDs is $\sigma$ and the transition energy at the QD maximum distribution of the $i$th optical transition is $E_{\text{max}}^i$, then $D(E')$ is given by [17]:

$$D(E') = \frac{s_i^{\text{eff}}}{\nu_{\dot{d}ot}^{\text{eff}}} \left( \frac{1}{2\pi \sigma^2} \right)^{1/2} \exp \left( -\frac{(E' - E_{\text{max}}^i)^2}{2\sigma^2} \right)$$

(6)

Where $s_i$ represents the number of degeneracy at each QD state. For QDs $s_i = 2$ for the ground state, and $s_i = 4$ for other excited states. $\nu_{\dot{d}ot}^{\text{eff}}$ represent the effective volume of QDs. If the areal density of QDs is $N_0$ and the average height of QDs is $h$ then, the effective volume is expressed as $v_{d\dot{ot}}^{\text{eff}} = h/N_0$.

In general, the Lorentzian line shape function $L_g(E', \hbar \omega)$ for material gain is used in Eq. (5). However, the Lorentzian line shape function is not accurate. So, instead the Gaussian line shape function is used for the QD gain, when the variance of the linewidth is defined as $\gamma$, and the Gaussian lineshape function is given by [17],

$$L_g(E', \hbar \omega) = \frac{1}{(2\pi \gamma^2)^{1/2}} \exp \left( -\frac{(E' - \hbar \omega)^2}{2\gamma^2} \right)$$

(7)

5. TM mode Momentum Matrix Element of QD Nanolaser

In Eq. (5), the term $|\hat{d}.p_e|\dot{}$ is the momentum matrix of QDs and it depends on the polarization of light. Because we are dealing with metal-coated structure so, only the momentum matrix element for TM polarization in the case of $(e - hh)$ transition was taken. To derive it, the momentum matrix element of QDs, first, can be written from the relation [21],

$$\langle |\hat{d}.p_{e-hh}|^2 \rangle = \frac{1}{2\pi} \int_0^{2\pi} d\phi \langle \hat{d}.p_{e-hh} \rangle = \frac{2}{3} \sin^2\theta \frac{M_b^2}{E_{c\text{mLit}}^2}$$

(8)

The angular factor $\cos^2\theta$ can be related to the electron or hole wave vectors in the y-direction as follows [26],

$$\cos^2\theta = \frac{\text{Quantized energy level in conduction band in } y\text{-direction}}{\text{Total energy levels}} = \frac{k_y^2}{k^2} = \frac{E_{c\text{ym}}}{E_{c\text{mLit}}}$$

(9)

As a result, the momentum matrix elements of the QD nanolaser, for TM mode becomes,

$$\langle |\hat{d}.p_{e-hh}|^2 \rangle = \frac{3}{2} \left( 1 - \cos^2\theta \right) M_b^2 = \frac{3}{2} \left( 1 - \frac{E_{c\text{ym}}}{E_{c\text{mLit}}} \right) M_b^2$$

(10)

Where $M_b^2 = \left( \frac{m_e}{\varepsilon_r} \right) E_p$, and $E_p$ is the optical matrix energy parameter.
6. Results and Discussion

Figure 5 (a) shows Fermi energy in CB, $F_c$, for the studied structure. For the conventional QD laser (red curve) i.e., QD-WL structure, a high $F_c$ was obtained. Including the barrier in the calculations i.e., QD-WL-B structure, which is also the case of conventional QD laser, (blue dotted curve) did not change the situation. Fig. 5 (b) shows the case of QD plasmonic nanolaser structure when the structure was covered by a metal (Ag). In this case, the waveguide Fermi energy $F_c$ curve same as the first case of conventional QD-WL shown in Fig. 5 (a). Including the barrier in the calculation i.e., QD-WL-B-M structure (blue dotted curve in Fig. 5 (b)) do not change the waveguide Fermi energy, as well.

![Figure 5](image)

**Figure 5.** Quasi-Fermi level in the conduction band including (a) QD-WL (solid red), and QD-WL-B (blue dashed) (b) QD-WL-M (solid red), and QD-WL-B-M (blue dashed).

Figure. 6 shows the Fermi energy in VB, $F_v$, of QD structure which is studied for the above mentioned structures. In figure 6 (a), first, $F_v$ in QD-WL structure (conventional QD laser) was shown near the top of VB. Then consider the barrier in the calculations as in the blue curve (QD-WL-B structure) shifts $F_v$ far from the band-edge of VB by more than 250meV. Figure. 6 (b) shows $F_v$ after adding the metal (yellow curve) i.e. the waveguide Fermi energy of plasmonic QD nanolaser structure (QD-WL-M structure). Here, $F_v$ goes down deeper than that in QD-WL structure in figure 6 (a) by approximately 315meV. Including B (i.e. QD-WL-B-M structure) in the calculations of $F_v$ in QD nanolaser structure takes $F_v$ deepest from QD-WL-M structure by approximately 1meV. So the main change in $F_v$ comes from adding metal. This may be attributed to the work function of the metal which makes Fermi level depinning.

![Figure 6](image)

**Figure 6.** Quasi-Fermi level in valence band in (a) QD-WL and QD-WL-B (b) inserting M to the structures.
Figure 7 shows gain for conventional QD laser (QD-WL), red curve, compared with the case when the barrier layer was included (QD-WL-B) in the calculations, blue curve. The result of QD-WL structure is in the range of Grundmann and Bimberg results [27]. Including B in the calculations (QD-WL-B) increases gain by more one order. This latter result was in the range of Ref. [28] results. The peak wavelength was also blue shifted by approximately 10 nm. This refers that barrier must be included in the calculation. This is with conclusion of the work in Ref. [20] where they find that including WL and B explains the results well since due their importance in controlling both static and dynamic characteristics. Figure 8 shows gain for plasmonic QD nanolaser where the conventional structure was covered with noble metal (Ag) (i.e. QD-WL-M structure). The gain was increased by 10 orders (yellow curve- its peak- $7 \times 10^{16}$ cm$^{-1}$) when metal was added compared with conventional QD laser in figure 7. Including barrier in the calculations (i.e. QD-WL-B-M structure) increases gain to $14 \times 10^{17}$ cm$^{-1}$ (magenta curve). This value of QD-WL-M gain was in the range of [15], where this work deals with the MSM structure also (but with bulk active region). Note that the value of gain obtained here overcomes the electron scattering losses ($10^{15}$fs) [29] which promises in high gain, high power and high speed applications.

![Figure 7. Gain for conventional QD laser: QD-WL (red curve) and QD-WL-B (blue curve).](image1.png)

![Figure 8. Gain spectra for plasmonic QD nanolaser: QD-WL-M (yellow curve), and QD-WL-B-M (magenta curve).](image2.png)

Figures 7 and 8 can also be viewed from results of figures 5 and 6. The VB Fermi energy $F_p$ in QD-WL-M and QD-WL-B-M structures goes deeper compared with $F_p$ in the structures that not considers M. Thus, for Fermi levels in metallic guiding structures immerse $F_p$ deep in VB which means that the transparency energy ($F_c - F_p$) lies near the VB edge of GaAs barrier, so WL works here as a reservoir for VB QD states and they are fully occupied which refers to an efficient hole contribution. This gives higher gain. Ordinary QD structures suffer from weak hole contribution (which requires p-doping) [18]. This gives higher gain. The above results were coinciding with the conclusion of [30]. They find experimentally that for the metal/semiconductor contacts, a high parasitic resistance was formed due to the potential barrier. Therefore, to improve the performance one must reduce the metal/semiconductor contact resistivity. Schottky barrier heights ($q\Phi_m$) must be reduced to get a low resistivity. Pinning Fermi-level close to VB stiffs the low ($q\Phi_m$). Achieving low ($q\Phi_m$) can be done by modulating it through the addition of an ultrathin insulator layer between semiconductor/metal [30].
7. Conclusions
In this work, the gain from quantum dot (QD) nanolaser was studied. MSM plasmonic structure was with QD semiconductor active region. The contribution of these layers and QD active region layers (QD, wetting layer and barrier) to the gain were considered. The required structure parameters are predicted from the band alignment between layers. TM Momentum matrix element in QD structure was formulated. The contribution of metal (Ag) on the Fermi energies of QD structure was formulated. It is shown that covering the structure by a metal makes WL works as a reservoir for VB QD states and they becomes fully occupied which refers to an efficient hole contribution. This increases the gain to a huge value compared with that obtained from conventional QD laser. The gain obtained here overcomes the electron scattering losses, which promises in high gain, high power and high speed applications.

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