Piezoelectric constant temperature dependence in strained [111]-oriented zinc-blende MQW-SOAs

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Received Month X, XXXX; accepted Month X, XXXX; posted online Month X, XXXX

Here we present a study of the effective piezoelectric constant ($e_{14}$) temperature dependence in strained [111]-oriented zinc-blende quantum wells (QWs) embedded within a semiconductor optical amplifier (SOA). For it, we determined $e_{14}$ using a method insensitive to the segregation phenomenon and to the temperature dependence of the bandgap energy, which requires neither fitting parameters nor temperature-dependent expressions for energy and out-of-plane effective masses of electrons and heavy holes. An $e_{14} = -0.0534 \pm 0.0040 \text{C} \cdot \text{m}^{-2}$ at 23°C was obtained for an SOA with 1.2 nm [111]-oriented strained In$_{0.687}$Ga$_{0.313}$As/In$_{0.807}$Ga$_{0.193}$As$_{0.504}$P$_{0.496}$ QWs. Unlike previously published works where $e_{14}$ magnitude increases as temperature rises, we extracted an $e_{14}$ magnitude that decreases as temperature increases.

**Keywords:** Piezoelectric constant, pyroelectric effect, quantum-confined Stark effect, excitons, semiconductor optical amplifiers, strained [111]-oriented zinc-blende quantum wells.

DOI: 10.3788/COLXXXXXX.XXXXXX.

**Introduction**

Due to the abrupt changes in absorption and refractive index that the quantum-confined Stark effect (QCSE) can potentially induce in a low-dimensional structure, this mechanism has excellent potential to develop ultra-fast all-optical functions for telecommunications systems using strained [111]-oriented zinc-blende multiple quantum well semiconductor optical amplifiers (MQW-SOAs) [1-2]. Indeed, these amplifiers, compared to the massive ones, exhibit higher differential gains, lower noise figures, and notably, an internal piezoelectric field that is mainly responsible for the QCSE when they are unbiased [3-4]. Therefore, to estimate the temperature dependence of the QCSE in MQW-SOAs and thus be able to use it as a contribution to tune the energy of the excitonic resonances where required for a specific application, it is crucial to determine the temperature dependence of the piezoelectric constant $e_{14}$. Some authors estimate $e_{14}$ using linear interpolation between the piezoelectric constant values of the relevant binary semiconductors of the alloy of the quantum wells (QWs) [3, 5]. Nevertheless, this procedure generates larger $e_{14}$ values than those obtained experimentally. Concerning the piezoelectric constant experimental determination in QWs, typically, $e_{14}$ is used as an adjustment parameter in theoretical models to fit the calculated values of the energies, of determined electronic transitions affected by the QCSE, to those obtained experimentally [6]. $e_{14}$ is also estimated by extracting key parameters from the Franz–Keldysh oscillations that allow its indirect determination [7]. However, in structures where, during the growth of the monolayers of the QW alloy, the surface segregation phenomenon can occur, the $e_{14}$ experimental determination becomes complex since this phenomenon produces a blue shift of the fundamental transition energy [8-10]. Therefore, methods used for determining $e_{14}$, based on calculations of energy levels, should consider this effect, although it is rarely included in them, probably because it substantially increases their degree of difficulty. Furthermore, when these methods are used to calculate $e_{14}$ as a function of temperature, they have the drawback that temperature also has a marked effect on the bandgap energy of the material constituting the QWs. Thus, as the temperature fluctuates, the energy of the electronic transitions or the extremes of the Franz–Keldysh oscillations is simultaneously affected by two remarkable effects: the temperature dependence that the bandgap energy presents and that exhibited by the piezoelectric constant. These simultaneous effects may generate erroneous $e_{14}$ experimental results or, at best, complicate its experimental determination.

Here, we use a simple method for experimentally determining the effective piezoelectric constant $e_{14}$, as a function of temperature, in strained zinc-blende QWs, grown along the 111 direction, of SOAs with a p-iMQW-n diode structure. Because the surface segregation phenomenon can impose a profile of values on $e_{14}$, by effective piezoelectric constant, we mean the global magnitude that is assigned to $e_{14}$. The used method, based on the determination of the relative Stark shifts that the QCSE induces in the fundamental excitonic resonance when the electrodes of the MQW-SOA under test are short-circuited, is insensitive to the variation of the bandgap energy with temperature. Likewise, the method is insensitive to the bandgap energy shift that may cause the surface segregation phenomenon. Even though the method was used to determine $e_{14}$ in an MQW-SOA, it can be applied to any p-iMQW-n diode structure with electrodes and strained identical zinc-blende QWs grown along 111 direction. In particular, we estimated $e_{14}$ in a temperature range of interest for telecommunication applications (18 – 28°C).

**Method**

In strained zinc-blende QWs, grown along 111 direction, of unbiased SOAs with a p-iMQW-n diode structure, the excitonic transition energy from the first electronic state to the first heavy-hole state (1s e-
determined experimentally as a function of optical 
photogenerated electron-hole pairs inside and outside 
contact potential difference, piezoelectric fields in the 
QWs, which can be estimated, and permittivity, \( \varepsilon \), is the piezoelectric field 
QWs, \( w \) is the width of the QWs, \( o \) is the vacuum 
static dielectric constants of 
the intrinsic layer and the QW layers, respectively, 
where \( \varepsilon_{s} \) and \( \varepsilon_{w} \) are the static 
dielectric constants of the intrinsic layer and the QW layers, respectively, \( L_{i} \) is the intrinsic region thickness, \( m \) is the number of 
QWs, \( L_{w} \) is the width of the QWs, \( \varepsilon_{0} \) is the vacuum 
permittivity, \( \eta_{w} \) is the shear strain 
times \( 2 \sqrt{3} (\varepsilon_{w} / \varepsilon_{0})^{-1} \) defined as 

\[
\eta_{w} = 2 \sqrt{3} \left( \frac{C_{11_{w}} + 2 C_{12_{w}} + 4 C_{44_{w}}}{\varepsilon_{w} \varepsilon_{0}} \right) \varepsilon_{s},
\]

being \( \varepsilon_{s} \), the lattice mismatch strain, \( C_{11_{w}} \), \( C_{12_{w}} \), and \( C_{44_{w}} \) the elastic stiffness coefficients of the material of the QWs, which can be estimated, as well as \( \varepsilon_{s} \), and \( \varepsilon_{w} \), by Vergard's Law [4]. Furthermore, in Eq. (2), \( V_{b_{w}}(T) \) is the effective built-in potential drop across the p–i–n diode, which is a function of temperature, 
contact potential difference, piezoelectric fields in the 
QWs, and electric fields created by dipoles formed by 
photogenerated electron-hole pairs inside and outside the 
QWs (in-well and long-range screening fields). It is 
noteworthy that, at temperature \( T \), \( V_{b_{w}}(T) \) can be 
determined experimentally as a function of optical 
power using a digital multimeter operating in the 
diode-test mode with its test leads connected between 
the MQW-SOA electrodes in such a way that it is 
forward-biased.

Taking into account that \( F_{w} \) causes a negligible 
change in \( E_{b} \), from Eq. (1), the energy difference 
(\( \Delta E_{x_{x_{a}}-x_{x_{b}}} \) existing between the 1S_{e-hh} ER 
energies under open- and short- circuit conditions 
(OCC and SCC) becomes practically equal to the total 
Stark shift difference (\( \Delta E_{x_{x_{a}}-x_{x_{b}}} \) experiencing 1S_{e-hh} ER under OCC and SCC [11]. Indeed, since the 
energies \( E_{x_{a}} \) and \( E_{x_{b}} \) are defined by Eq. (1), their 
difference, for the same temperature, causes the 
cancellation of \( \Delta E_{b} \) and \( \Delta E_{s} \) and therefore, of the 
effects of temperature and segregation phenomenon 
on \( E_{b} \); consequently, \( \Delta E_{x_{x_{a}}-x_{x_{b}}} \) is given in eV by [11,12]

\[
\Delta E_{x_{x_{a}}-x_{x_{b}}} = \Delta E_{x_{x_{a}}} - \Delta E_{x_{x_{b}}} = \left(-\tilde{A}_{e-hh} L_{w} F_{w}^{2} + Q_{e} L_{w} F_{w} - \frac{2}{\varepsilon_{w}}(\tilde{A}_{e-hh} L_{w} F_{w}^{2})\right),
\]

where \( \tilde{A}_{e-hh} \) is a function of the electron (heavy hole) 
out-of-plane effective mass in the QWs and the ground 
state energy shift enhancement factor, at low fields, 
due to the finite value of the barrier height for 
electrons (heavy holes) [12]. Besides, \( F_{w} \) is the 
maximum value of \( F_{i} \), which is obtained when the 
amplifier electrodes are short-circuited and thus 
\( V_{b_{w}} = 0 \) (see Eq. (2)), \( Q_{e} \) is the elementary charge 
times 6.2415 \times 10^{18} \text{ eV} / \text{J}, and \( L_{w} \) is the 
separation, induced by \( F_{w} \), between the QWs, of the 
photogenerated electron and hole wave functions. For 
input powers that, under OCC, produce such a 
piezoelectric field screening that the 1S_{e-hh} ER 
energy undergoes a shift of less than 1.0 meV, it can be 
assumed \( F_{w} \) is strong enough for \( F_{i} \) to induce a 
spatial separation between the photogenerated 
electron and hole wave functions close to the largest 
possible \( (L_{w}) \) [4]. Under these conditions, \( L_{w} \) \( \approx L_{w} \); 
thus, substituting Eq. (2) into Eq. (4) and solving it for 
\( e_{14_{w}} \) results in the following expression:

\[
\eta_{w} = \frac{2 \sqrt{3} \left( C_{11_{w}} + 2 C_{12_{w}} + 4 C_{44_{w}} \right) \varepsilon_{s}}{\varepsilon_{w} \varepsilon_{0}}.
\]

Here \( \Delta E_{x_{x_{a}}} \) and \( V_{b_{w}} \) are the values that \( \Delta E_{x_{x_{a}}-x_{x_{b}}} \) and \( V_{b_{w}} \) assume, respectively, when the input power is \( P_{n} \). On the other hand, by using two input powers, \( P_{1} \) and \( P_{2} \), a system of two coupled equations can be obtained from Eq. (5), whose resolution results in the 
following expression for \( \tilde{A}_{e-hh} \):

\[
\tilde{A}_{e-hh} = \frac{-2 W_{e-hh} + L_{w} Q_{e} (V_{s_{1}}^{2} - V_{s_{2}}^{2}) \varepsilon_{s} / \varepsilon_{w} L_{i}}{4 V_{s_{1}} V_{s_{2}} L_{w} F_{i}^{2} (V_{s_{1}} - V_{s_{2}}) \varepsilon_{i}^{2} / \varepsilon_{w}^{2}}
\]
input power constant at \( -\) For each examined range of \( \pm 28 \) \( ^\circ \text{C} \), the continuum spectrum, are launched in co-

For this purpose, we use the setup shown in Fig. 1, via an optical spectrum analyzer (OSA), with a wavelength accuracy of \( \Delta \lambda \text{OSA} = \pm 0.02 \) nm (see Fig. 1). Fig. 2 shows the obtained transmission spectra, around \( 1S_{\text{e-hh}} \) ER, for the probe beam when the total input power was \( P_{\text{in}} = -15.9 \) dBm and \( P_{\text{out}} = -4.53 \) dBm, and the amplifier temperature was set at 18, 23, and 28 \( ^\circ \text{C} \) under OCC. For the same temperatures but under SCC, Fig. 2 shows only transmission spectra obtained with a total input power of \(-15.9 \) dBm since these are identical to those acquired with a total input power of \(-4.53 \) dBm. Effectively, under steady-state and SCC, \( V_{\text{th_a}} = 0 \) and \( F_{\text{th}} \) becomes input power independent because the photogenerated carriers quickly escape from the QWs and are immediately drained by the MQW-SOA electrodes. Consequently, there are no free carriers inside or outside the QWs can establish piezoelectric field screening mechanisms modifying the QCSE [4].

**Results and discussion**

Now, we use the procedure explained above for estimating the \( \epsilon_{14} \) value within the \([111]\)-oriented strained \( \text{In}_{0.687}\text{Ga}_{0.313}\text{As} / \text{In}_{0.807}\text{Ga}_{0.192}\text{As}_{0.304}\text{P}_{0.696} \) QWs of an unbiased MQW-SOA. The amplifier comprises a \( p^-\) \( i \) MQW-\( n \) structure with a 2.2 \( \mu \text{m} \) wide and 0.1 \( \mu \text{m} \) thick intrinsic active region incorporating a central section, with eight QWs separated by seven barriers, clad on both sides by a 28.4 \( \mu \text{m} \) thick undoped \( \text{In}_{0.807}\text{Ga}_{0.192}\text{As}_{0.304}\text{P}_{0.696} \) separate confinement heterostructure (SCH). The QW and barrier widths are nominally 1.2 and 4.8 \( \text{nm} \), respectively, and QWs are subjected to a compressive lattice mismatch strain of \( \epsilon_s = -0.0142 \). Besides, \( \frac{c_i}{c_o} = 0.904 \) and \( c_u = 14.122 \).

By using the relations in Eq. (3) and Eqs. (6)–(9) into Eq. (5), and measuring \( V_{\text{th_a}} \) and \( \Delta \epsilon_{\text{th_a}} \) for different temperatures, it is possible to determine \( \epsilon_{14}(T) \).

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First, we determine \( \Delta \epsilon_{\text{th_a}} = \epsilon_{\text{th_a}} - \epsilon_{\text{th}} \) when the total input power is \( P_{\text{in}} \) in the temperature range of 18 to 28 \( ^\circ \text{C} \). For this purpose, we use the setup shown in Fig. 1, where a probe beam and a control beam, whose photon energy (1569 nm) is located well within the continuum spectrum, are launched in counterpropagation into the amplifier with horizontal linear polarization. At a specific temperature within the range of 18 to 28 \( ^\circ \text{C} \), the probe beam wavelength is swept across the \( 1S_{\text{e-hh}} \) ER spectral width, keeping its input power constant at \(-15.9 \) dBm. For each examined wavelength and each total input power, defined as the sum of the input powers of the control and probe beams, the probe beam power at the amplifier output is determined under SCC and OCC (using switch S1 in Fig. 1), via an optical spectrum analyzer (OSA), with a wavelength accuracy of \( \Delta \lambda \text{OSA} = \pm 0.02 \) nm (see Fig. 1). Fig. 2 shows the obtained transmission spectra, around \( 1S_{\text{e-hh}} \) ER, for the probe beam when the total input power was \( P_{\text{in}} = -15.9 \) dBm and \( P_{\text{out}} = -4.53 \) dBm, and the amplifier temperature was set at 18, 23, and 28 \( ^\circ \text{C} \) under OCC. For the same temperatures but under SCC, Fig. 2 shows only transmission spectra obtained with a total input power of \(-15.9 \) dBm since these are identical to those acquired with a total input power of \(-4.53 \) dBm. Effectively, under steady-state and SCC, \( V_{\text{th_a}} = 0 \) and \( F_{\text{th}} \) becomes input power independent because the photogenerated carriers quickly escape from the QWs and are immediately drained by the MQW-SOA electrodes. Consequently, there are no free carriers inside or outside the QWs can establish piezoelectric field screening mechanisms modifying the QCSE [4].

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**Fig. 2.** Transmission spectra for \( P_{\text{in}} = -15.9 \) dBm and \( P_{\text{out}} = -4.53 \) dBm (indicated with solid and dashed arrows, respectively) at 18, 23, and 28 \( ^\circ \text{C} \) under SCC (upper spectra) and OCC (lower spectra). Marks and traces are the measured values and their interpolations.

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By using the relations in Eq. (3) and Eqs. (6)–(9) into Eq. (5), and measuring \( V_{\text{th_a}} \) and \( \Delta \epsilon_{\text{th_a}} \) for different temperatures, it is possible to determine \( \epsilon_{14}(T) \).
Now, using Eqs. (3) and (5)–(9), as well as the found values for $\Delta E_{\text{el},2}$ and $V_{\text{th},2}$, $\varepsilon_{14}$ at 23 $^\circ$C can be determined. Similarly, $\varepsilon_{14}$ can be estimated for any temperature. For clarity, Fig. 2 only shows the transmission spectra for 18, 23, and 28 $^\circ$C; however, the experimental determination of the 1S$_{\text{c},hh}$ER energy under SCC ($E_{\text{sc}}$) and OCC ($E_{\text{oc},1}$) and the voltages $V_{\text{th},2}$ were performed for eleven temperatures. Expressedly, the MQW-SOA temperature was varied using a Peltier element (PE) and a thermoelectric temperature controller (TTC) with $\pm0.2$ $^\circ$C accuracy (see Fig. 1). The results are presented in Fig. 3, where the experimental data for $E_{\text{sc},1}$, $E_{\text{oc},1}$, and $V_{\text{th},2}$ are shown with their linear interpolations accompanied by their respective formulas.

Fig. 4 shows the $\varepsilon_{14}$, $A_{\text{hh}}$, and $\Delta E_{\text{sc}}$ values (open crosses), calculated as a function of temperature using Eqs. (3), (5)–(9), and the last term on the right-hand side (RHS) of Eq. (4) ($-\Delta A_{\text{hh}} L_{n}^{2} F_{\text{sc}}$) together with the experimentally obtained values of $E_{\text{sc},1}$ and $V_{\text{th},2}$ reported in Fig. 3 (marks).

$\Delta E_{\text{el}}$ and $\varepsilon_{14}$ have opposite temperature coefficients, and the parameter $\Delta E_{\text{el}}$ increases as the temperature increases. The parameter $\varepsilon_{14}$ tends to decrease as temperature increases. Indeed, as temperature rises, the electric dipole randomization increases; hence, the strain-induced polarization decreases together with $\varepsilon_{14}$.

It is relevant to mention that this behavior is contrary to that observed in other previously published works where the piezoelectric constant magnitude in In$_{x}$Ga$_{1-x}$As QWs increases as temperature increases, for which no convincing explanation has been presented [13-17]. To gain more insight into this contradictory aspect, we further investigate the behavior regarding temperature of the 1S$_{\text{c},hh}$ER total Stark shift under SCC ($\Delta E_{\text{sc}}$). As shown in the lower graph of Fig. 4, the $\Delta E_{\text{sc}}$ magnitude increases as the temperature increases. Vis-a-vis the behavior exhibited by $\varepsilon_{14}$, the $\Delta E_{\text{sc}}$ behavior concerning temperature would seem to be opposite to that expected since the $\Delta E_{\text{sc}}$ magnitude is directly proportional to $F_{\text{sc}}$, which is in turn directly proportional to $\varepsilon_{14}$ (see last terms on RHS of Eqs. (4) and (2) with $V_{\text{th},2}=0$). However, $\Delta E_{\text{sc}}$ also depends on the parameter $A_{\text{hh}}$ whose magnitude increases as the temperature increases, as shown in the middle graph of Fig. 4. Although $A_{\text{hh}}$ contributes linearly to the $\Delta E_{\text{sc}}$ magnitude, its growth rate with increasing temperature is strong enough to overcome the antagonistic rate of the quadratic contribution from $\varepsilon_{14}$; for this reason, the $\Delta E_{\text{sc}}$ magnitude increases as temperature increases. The parameter $A_{\text{hh}}$, which can be determined by performing indirect measurements and applying Eq. (6), is physically a function of the out-of-plane effective masses ($m_{\text{c},hh}$) and the ground state energy shift enhancement factors ($\Omega_{\text{c},hh}$), due to the finite value of the barrier height, of electrons and heavy holes [12]. Consequently, in models where $m_{\text{c},hh}$ and $\Omega_{\text{c},hh}$ are used explicitly instead of $A_{\text{hh}}$, it becomes essential.

Fig. 3. $E_{\text{sc},1}$ and $V_{\text{th},2}$ vs temperature. Marks and traces are the measured values and their linear interpolations accompanied by their respective formulas.

Fig. 4. $\varepsilon_{14}$, $A_{\text{hh}}$, and $\Delta E_{\text{sc}}$ vs temperature (upper, middle, and lower graphs) calculated using experimentally obtained values (open crosses) and interpolated values (open circles and their interpolations with solid lines) of $E_{\text{sc},1}$ and $V_{\text{th},2}$.

$\pm0.004$ C m$^{-2}$, which is similar to that obtained by other methods extracting the $\varepsilon_{14}$ value [13]. Besides, as expected, these $\varepsilon_{14}$ values, and in general all those reported in the upper graph of Fig. 4, evidence that the $\varepsilon_{14}$ magnitude tends to decrease as temperature increases. Indeed, as temperature rises, the electric dipole randomization increases; hence, the strain-induced polarization decreases together with $\varepsilon_{14}$. 

It is relevant to mention that this behavior is contrary to that observed in other previously published works where the piezoelectric constant magnitude in In$_{x}$Ga$_{1-x}$As QWs increases as temperature increases, for which no convincing explanation has been presented [13-17]. To gain more insight into this contradictory aspect, we further investigate the behavior regarding temperature of the 1S$_{\text{c},hh}$ER total Stark shift under SCC ($\Delta E_{\text{sc}}$). As shown in the lower graph of Fig. 4, the $\Delta E_{\text{sc}}$ magnitude increases as the temperature increases. Vis-a-vis the behavior exhibited by $\varepsilon_{14}$, the $\Delta E_{\text{sc}}$ behavior concerning temperature would seem to be opposite to that expected since the $\Delta E_{\text{sc}}$ magnitude is directly proportional to $F_{\text{sc}}$, which is in turn directly proportional to $\varepsilon_{14}$ (see last terms on RHS of Eqs. (4) and (2) with $V_{\text{th},2}=0$). However, $\Delta E_{\text{sc}}$ also depends on the parameter $A_{\text{hh}}$ whose magnitude increases as the temperature increases, as shown in the middle graph of Fig. 4. Although $A_{\text{hh}}$ contributes linearly to the $\Delta E_{\text{sc}}$ magnitude, its growth rate with increasing temperature is strong enough to overcome the antagonistic rate of the quadratic contribution from $\varepsilon_{14}$; for this reason, the $\Delta E_{\text{sc}}$ magnitude increases as temperature increases. The parameter $A_{\text{hh}}$, which can be determined by performing indirect measurements and applying Eq. (6), is physically a function of the out-of-plane effective masses ($m_{\text{c},hh}$) and the ground state energy shift enhancement factors ($\Omega_{\text{c},hh}$), due to the finite value of the barrier height, of electrons and heavy holes [12]. Consequently, in models where $m_{\text{c},hh}$ and $\Omega_{\text{c},hh}$ are used explicitly instead of $A_{\text{hh}}$, it becomes essential.
that these parameters are a function of temperature. Otherwise, the change that the 1S\textsubscript{eh}ER total Stark shift would undergo with temperature would be solely attributed to $\varepsilon_4$, and vice versa: if the Stark shift behavior were used to determine that of $\varepsilon_4$, an erroneous comportment of $\varepsilon_4$ contrary to that found in this work, would be obtained. We speculate that the discrepancy between the piezoelectric constant behavior regarding temperature estimated in this work and that reported by other authors might be due to the omission of the temperature dependences of $n_{\text{e-hh}}$ and electron (heavy hole) energy in the QWs, or an imprecise description of them, possibly because of the lack of detailed reports on these issues.

Finally, Fig. 2 shows that by varying temperature from 18 to 28 °C, the 1S\textsubscript{eh}ER operation energy can be tuned $\pm$ 4 meV, and then, under OCC, fluctuating the input power from $-15.9$ to $5 \text{ dBm}$, this resonance can be shifted $\pm$ 3.7 meV, as shown in Fig. 5. It is important to note that if the input signal were composed of pulses whose duration was less than the escape time of the carriers in the QWs plus the time it takes them to drain through the circuit formed by parasitic elements and the amplifier electrodes, under SCC, the power of each input pulse would also shift 1S\textsubscript{eh}ER.

![Graph](image)

Fig. 5. 1S\textsubscript{eh}ER energy vs total input power at 18, 23, and 28 °C. Marks and traces are the measured values and their interpolations.

This opens the possibility of devising ultra-fast all-optical applications using unbiased MQW-SOAs since there would be no free carriers that would generate slow tails in the falling edges of the output pulses as might occur under OCC, notably with high input powers. A study of the Stark effect dynamics under SCC and OCC is currently in progress.

**Conclusion**

Here, we presented a procedure for determining the effective piezoelectric constant value of the [111]-oriented strained In\textsubscript{1-x}Ga\textsubscript{x}As/In\textsubscript{1-x}Ga\textsubscript{x}As/Al\textsubscript{y}P\textsubscript{1-y} QWs of an MQW-SOA. Remarkably, the proposed method is insensitive to the temperature dependence of the bandgap energy and the segregation phenomenon. Likewise, it requires neither fitting parameters nor temperature-dependent expressions for energy and out-of-plane effective masses of electrons and heavy holes. When the procedure was applied to the MQW-SOA under study, a value of $\varepsilon_4 = -0.0534 \pm 0.0040 \text{ C-m}^{-2}$ at 23 °C was obtained. Unlike previously published methods where the piezoelectric constant magnitude increases as temperature rises without convincing explanation, we extracted an $\varepsilon_4$ magnitude that decreases as temperature increases. Even though the method was specially designed for experimentally determining $\varepsilon_4$ in MQW-SOAs, it can be applied to any p-iMQW-n structure with electrodes and strained [111]-oriented zinc-blende QWs. Finally, we found that by varying temperature, the 1S\textsubscript{eh}ER operation energy can be tuned, and then, fluctuating the input power, this resonance can be significantly shifted. This enables to devise all-optical applications based on QCSE in unbiased MQW-SOAs. Thus, for example, the method can be applied to other MQW-SOAs, intended to implement all-optical functions based on the QCSE, to predict the shift of their 1S\textsubscript{eh}ER with temperature, or to indirectly deduce how temperature will affect the undesirable effects that QCSE causes in some MQW LEDs.

**References**


Funding Sources
Partial financial support was received from the Mexican Council of Science and Technology (CONACYT) (Grant SEP-CONACYT-2016-01-285030 and doctoral grant 804835).