Infra Red Radiation Induced by Fracture of Elemental and III-V Semiconductors


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Abstract

The present paper reports the transient behavior of mechanoluminescence of elemental and III–V semiconductors. When an elemental and III–V semiconductor is cleaved, initially the ML intensity increases with time, attains a peak value $I_m$ at the time $t_m$ corresponding to completion of the cleavage and then it decreases exponentially with time, in which the decay time of ML depends on the type of signal emitted. Three types of signal are produced during the cleavage of elemental and III–V semiconductors. Type A signals arises due to the cleavage-induced population of the bulk conduction band and shallow traps and their subsequent de-excitation. Type B signal is produced due to the cleavage–induced population of the surfaces states and their subsequent de-excitation and type C signal occurs due to the cleavage-induced population of the defect centers and their subsequent de-excitation. The peak ML intensity $I_m$ and the total ML intensity $I_T$ increase directly with the area of the newly created surfaces of crystals. The wavelength of the light induced by cleavage of elemental and III-V semiconductors lies in the infrared region. Expressions are derived for different parameter of ML of elemental and III–V semiconductors, whereby a good correlation is found between the theoretical and experimental results.
Introduction
In general, the mechanoluminescence produced during fracture of most of the organic and inorganic crystals contains light in the visible and ultraviolet regions. However, the fracture of certain solids produces the light in the infrared regions. In this connection, the ML of elemental and III–V semiconductors has been interesting.

Silicon emitted IR from 3300 nm to 4800nm upon fracture but not upon abrasion [1]. Because abrasion did not stimulate the emission, it was assigned to surface rather than blackbody radiation. Using filters to isolate the bands, plus life time and the effect of air, Li, McAlpine and Hanemann concluded that the long-lived near IR band was from bulk-band gap transitions, the long–lived mid-IR band was from surface state transitions and the short-lived near-IR band was from surface defect [1, 2, 3]. Gallium arsenide and indium phosphide also gave IR emissions on cleavage [2]. Experiments similar to those for silicon showed that indium phosphide’s band at 1000 nm, found only at vacuum, was from bulk-band gap transitions, and the band at 660 nm found both in vacuum and air from surface defects [3]. Germanium films crystallized and lifted off the surface by bring pricked with a sharp point [4] mechanoluminesced sufficiently to be photographed, but only with infrared films. Filters revealed two bands of different lifetimes and different air-sensitivities similar to those observed for silicon [3]. Silicon-germanium mixture showed similar emissions – a high-energy, short-lived air-insensitive band from surface defects and a lower energy long-lived (indirect) bulk-band gap emission seen only under vacuum [3].

The present paper reports the theoretical approach made on the infrared radiation induced by fracture of elemental and III–V semiconductors, and makes a comparison between the theoretical and experimental results.

Mechanism of The Infrared Radiation Induced by Fracture of Elemental and III- V Semiconductors
For the cleavage-induced ML excitation in elemental and III- V semiconductors, the following model may be proposed: (i) Charging of newly created surfaces, (ii) Thermal generation of charge carriers, (iii) Recombination of fracture-generated defects, and (iv) Formation of crack induced localized states. The suitability of first three models can be eliminated on the basis of experimental results. Thus, the forth model seems to be suitable for the infrared emission induced by the fracture of elemental and III – V semiconductor.

According to their model, as the atoms are drawn away from each other in an advancing crack tip, the decreasing wave-function overlap across the crack may results in the localized states. Anderson localization is expected to result from variations in crack width and from mismatch across the crack due to shear displacements [5]. Decreasing wave-function overlap is generally associated with increasing electron energy. If the energy of those localized states approaches that of the conduction band, transition through conduction band via tunneling would be possible, creating minority carriers. These transitions may be further facilitated by shifts in the conduction band energy due to high stress field near the crack tip.
Subsequently, the radiative recombination of electrons and holes may give rise to mechanoluminescence.

Lemke and Haneman [6] have identified states which they associated with wavefunction overlap across narrow indentation cracks in Si. Their electron-spin resonance measurement indicated the presence of about $10^{14}$ spins/cm$^2$ of crack area. In contrast, well cleaved surfaces show very low spin densities. The high density of paramagnetic states suggests that “normal” surface relaxation is hindered while the crack width is less than about 0.5 nm. In crack propagation, particularly involving mixed fracture modes where crack opening displacements immediately behind the crack tip are small, a similar hindrance may increase the probability of high-energy excitons.

Electronic excitations resulting in charge carrier production would most likely be associated with localized states of energy greater than or equal to that of the conduction band. Localization reduces the probability of recombination with valance band holes and thus increases the probability of transition to the conduction band. The relatively low acceptor concentration in the material used also limits the recombination rate. The states involved in the excitation would probably be associated with surface defects or other localized phenomena.

The total numbers of photons produced during the creation of unit surface area are $3 \times 10^8$, $1.525 \times 10^{10}$, $7 \times 10^6$, and $3 \times 10^4$ for Ge, Si, InP, and GaAs semiconductors respectively [3]. The band gaps of Ge, Si, InP, and GeAs are 0.67, 1.14, 1.35 and 1.43 eV respectively. Except Ge, it follows that the number of photon emitted decreases with increasing energy of band gap. This fact supports the ML model involving formation of crack induced localized states. The low value of ML efficiency in Ge as compared to that in Si may probably due to the low value of the efficiency of radiative transition in this crystal.

Fig 1 shows the schematic diagram showing origin of luminescence due to the de-excitation of electrons excited by cleavage into bulk conduction band and shallow traps (A), into upper surface states (B), and at defect centers (C). As the decay time of signal A lies in between 300 to 500 μs, it seems that the de-excitation of shallow traps near the conduction band is also responsible for the emission of the signal A.

![Figure 1: Schematic diagram showing origins of luminescence due to de-excitation of electrons excited by cleavage into bulk conduction band or into upper surface states (after ref. [2]).](image)
Suppose a crystal having length L, breadth W and thickness H is cleaved along the plane parallel to the breadth side. If v is the average velocity of the crack, then the rate of creation of new surfaces is given by $2Wv$. If $Z_1$, $Z_2$ and $Z_3$ are the densities of excited electrons in the conduction band and shallow traps, and excited electron in the defects, respectively, for the creation of unit surface area, then the rate of generations $g_1$, $g_2$ and $g_3$, of electrons in the conduction band and shallow traps, excited surfaces states and excited defects centers, respectively may be expressed as

\[ g_1 = 2Z_1 Wv \]  
\[ g_2 = 2Z_2 Wv \]  
\[ g_3 = 2Z_3 Wv \]

As $\Delta n << n_0$ (the number of electrons in the conduction band in the equilibrium state), the electron hole recombination will be monomolecular type. It is to be noted that the bimolecular recombination takes place, when $\Delta n >> n_0$. If $\phi_1, \phi_2$ and $\phi_3$ are the rate constants for the recombination of the electrons from the localized states lying in the conduction bands and the shallow traps, surface states and defect centers, respectively, then we can write the following expressions:

\[ \frac{d\Delta n_1}{dt} = g_1 - \phi_1 \Delta n_1 \]  
\[ \frac{d\Delta n_2}{dt} = g_2 - \phi_2 \Delta n_2 \]  
\[ \frac{d\Delta n_3}{dt} = g_3 - \phi_3 \Delta n_3 \]

where, $\Delta n_1$, $\Delta n_2$ and $\Delta n_3$ are the changes in the number of electrons in the conduction band and shallow traps, surface states and defect centers at any time $t$.

Integrating equations (4), (5), (6) and taking $\Delta n_1 = 0$, $\Delta n_2 = 0$ and $\Delta n_3 = 0$ at $t = 0$, we get

\[ \Delta n_1 = \frac{g_1}{\phi_1} [1 - \exp(-\phi_1 t)] \]
\[ \Delta n_2 = \frac{g_2}{\phi_2} [1 - \exp(-\phi_2 t)] \]
\[ \Delta n_3 = \frac{g_3}{\phi_3} [1 - \exp(-\phi_3 t)] \]

If $\eta_1$, $\eta_2$ and $\eta_3$ are the efficiency for the electrons-hole radiative recombination for the signals A, B and C, respectively, then the ML intensity due to the transition of electrons from the conduction band and shallow traps, surface states and defect centres may be expressed by the following equations, respectively

\[ I_1 = \eta_1 \phi_1 \Delta n_1 = \eta_1 g_1 [1 - \exp(-\phi_1 t)] \]
\[ I_2 = \eta_2 \phi_2 \Delta n_2 = \eta_2 g_2 [1 - \exp(-\phi_2 t)] \]
And \( I_3 = n_3 \phi_3 \Delta \eta_3 = n_3 g_3 [1 - \exp(-\phi_3 t)] \) \hspace{1cm} (12)

It is seen from Eqs. (10) (11) and (12) that initially \( I_1, I_2 \) and \( I_3 \) should increase linearly with time and they should tend to attain saturation values.

**Rise of ML Intensity**

For \( \phi_1 t > t > \eta_1 \phi_1 \), \( \phi_2 t > t > \eta_2 \phi_2 \) and \( \phi_3 t > t > \eta_3 \phi_3 \), Eqs. (10), (11) and (12) can be expressed as

\[
I_{1r} = n_1 g_1 \phi_1 t = 2 n_1 Z_1 W v \phi_1 t \hspace{1cm} (13)
\]

\[
I_{2r} = n_2 g_2 \phi_2 t = 2 n_2 Z_2 W v \phi_2 t \hspace{1cm} (14)
\]

and, \( I_{3r} = n_3 g_3 \phi_3 t = 2 n_3 Z_3 W v \phi_3 t \hspace{1cm} (15) \)

It is evident from Eqs. (13), (14) and (15) that after the cleavage \( I_{1r}, I_{2r} \) and \( I_{3r} \) should increase linearly with time \( t \).

**Maximum Value \( I_m \) of the ML Intensity**

If \( t_m = \frac{H}{v} \), is the time at which cleavage of the crystals is completed and \( \phi_1 t_m << 1, \phi_2 t_m << 1 \) and \( \phi_3 t_m << 1 \), then Eqs. (13), (14) and (15) may be expressed as

\[
I_{1m} = n_1 g_1 \phi_1 t_m = 2 n_1 Z_1 W v \phi_1 t_m = \eta_1 \phi_1 A Z_1 \hspace{1cm} (16)
\]

\[
I_{2m} = n_2 g_2 \phi_2 t_m = 2 n_2 Z_2 W v \phi_2 t_m = \eta_2 \phi_2 A Z_2 \hspace{1cm} (17)
\]

And \( I_{3m} = n_3 g_3 \phi_3 t_m = 2 n_3 Z_3 W v \phi_3 t_m = \eta_3 \phi_3 A Z_3 \hspace{1cm} (18) \)

Equation (16), (17) and (18) indicate that \( I_{1m}, I_{2m} \) and \( I_{3m} \) should increase linearly with \( A \), where \( A = 2 W H \), is the area of newly created surfaces of the crystals. From Eqs. (16), (17) and (18), the maximum ML intensity may be expressed as

\[
I_m = (\eta_1 \phi_1 Z_1 + \eta_2 \phi_2 Z_2 + \eta_3 \phi_3 Z_3) A \hspace{1cm} (19)
\]

Equation (19) indicates that the resultant maximum value of the ML intensity should increase linearly with the area \( A \) of the newly created surfaces of the crystals.

**Decay of ML Intensity**

When the cleavage of the of the crystal will be completed, \( v = 0 \) or \( g_1 = 0, g_2 = 0 \) and \( g_3 = 0 \), and from Eqs. (4), (5) and (6), we get

\[
\frac{d \Delta n_1}{dt} = - \phi_1 \Delta n_1 \hspace{1cm} (20)
\]

\[
\frac{d \Delta n_2}{dt} = - \phi_2 \Delta n_2 \hspace{1cm} (21)
\]

\[
\frac{d \Delta n_3}{dt} = - \phi_3 \Delta n_3 \hspace{1cm} (22)
\]

For \( \phi_1 t_m << 1, \phi_2 t_m << 1 \) and \( \phi_3 t_m << 1 \), from Eqs. (7), (8) and (9), we get \( \Delta n_1 = g_1 t_m, \Delta n_2 = g_2 t_m \) and \( \Delta n_3 = g_3 t_m \) at \( t = t_m \). Thus the integration of Eqs. (20), (21) and (22) gives

\[
\Delta n_1 = g_1 t_m \exp(-\phi_1 (t-t_m)) \hspace{1cm} (23)
\]
\[ \Delta n_2 = g_2 t_m \exp[\phi_2 (t-t_m)] \]  
\[ \Delta n_3 = g_3 t_m \exp[-\phi_3 (t-t_m)] \]

Now, the decay of ML intensity may be expressed as
\[ I_{1d} = \eta_1 \phi_1 \Delta n_1 = \eta_1 g_1 \phi_1 t_m \exp[-\phi_1 (t-t_m)] \]  
\[ I_{2d} = \eta_2 \phi_2 \Delta n_2 = \eta_2 g_2 \phi_2 t_m \exp[-\phi_2 (t-t_m)] \]

and,  
\[ I_{3d} = \eta_3 \phi_3 \Delta n_3 = \eta_3 g_3 \phi_3 t_m \exp[-\phi_3 (t-t_m)] \]

or,  
\[ I_{1d} = I_{1m} \exp[-\phi_1 (t-t_m)] \]  
\[ I_{2d} = I_{2m} \exp[-\phi_2 (t-t_m)] \]  
\[ I_{3d} = I_{3m} \exp[-\phi_3 (t-t_m)] \]

where,  
\[ I_{1m} = \eta_1 \phi_1 A Z_1, \ I_{2m} = \eta_2 \phi_2 A Z_2 \] and  
\[ I_{3m} = \eta_3 \phi_3 A Z_3 \]

Equations (29), (30) and (31) indicate that \( I_1, I_2 \) and \( I_3 \) should decay exponentially with rate constants \( \phi_1, \phi_2 \) and \( \phi_3 \), respectively.

**Estimation of the Total ML Intensity \( I_T \)**

The total ML intensity is given by
\[ I_T = \frac{1}{0} \int_0^\infty (I_1 + I_2 + I_3) \ dt + \frac{1}{0} \int_0^\infty (I_{1d} + I_{2d} + I_{3d}) \ dt \]

From Eqs. (10), (11), (12), (26), (27) and (28), we get
\[ I_T = \left[ \eta_1 g_1 \left\{ t + \frac{\exp(-\phi_1 t)}{\phi_1} \right\} + \eta_2 g_2 \left\{ t + \frac{\exp(-\phi_2 t)}{\phi_2} \right\} + \eta_3 g_3 \left\{ t + \frac{\exp(-\phi_3 t)}{\phi_3} \right\} \right]_0^\infty + \left[ \eta_1 \phi_1 t_m \exp[-\phi_1 (t-t_m)] + \eta_2 \phi_2 g_2 t_m \exp[-\phi_2 (t-t_m)] + \eta_3 \phi_3 g_3 t_m \exp[-\phi_3 (t-t_m)] \right]_0^\infty \]

where, \( I_T = I_x \)

or, \[ I_T = \left[ \eta_1 g_1 \left\{ t + \frac{\exp(-\phi_1 t)}{\phi_1} \right\} + \frac{1}{\phi_1} \right] + \left[ \eta_2 g_2 \left\{ t + \frac{\exp(-\phi_2 t)}{\phi_2} \right\} + \frac{1}{\phi_2} \right] + \left[ \eta_3 g_3 \left\{ t + \frac{\exp(-\phi_3 t)}{\phi_3} \right\} + \frac{1}{\phi_3} \right] \]

or, \[ I_T = \left[ \eta_1 g_1 \left\{ 2t_m - \frac{1}{\phi_1} (1-\exp(-\phi_1 t_m)) \right\} + \eta_2 g_2 \left\{ 2t_m - \frac{1}{\phi_2} (1-\exp(-\phi_2 t_m)) \right\} + \eta_3 g_3 \left\{ 2t_m - \frac{1}{\phi_3} (1-\exp(-\phi_3 t_m)) \right\} \right] \]
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For $\phi_1 t_m << 1$, $\phi_2 t_m << 1$ and $\phi_3 t_m << 1$, $\{1-\exp(-\phi_1 t_m)\}=\phi_1 t_m$,
$\{1-\exp(-\phi_2 t_m)\}=\phi_2 t_m$ and $\{1-\exp(-\phi_3 t_m)\}=\phi_3 t_m$

Thus, $I_t = [\eta_1 g_1 + \eta_2 g_2 + \eta_3 g_3] t_m$
Or, $I_t = [\eta_1 Z_1 + \eta_2 Z_2 + \eta_3 Z_3] A$

\[ (34) \]

where, $g_1 t_m = Z_1 A$, $g_2 t_m = Z_2 A$ and $g_3 t_m = Z_3 A$

For a crystal having small value of $H$, total intensity may be expressed a by equation (34).

Experimental Support to the Proposed Theory
Hanemann [1] and Li [2, 7] have made, detailed measurement of the ML produced during cleavage of semiconductors. In those measurements the specimens in the form of thin wafer were cleaved, usually by bending over a knife-edge in a vacuum chamber with an appropriate photovoltaic detector mounted at a few mm above the crack. For bending, the specimen was tightly clamped between steel or aluminum blocks. For uniaxial tension, they were held by a vacuum epoxy (“Torr seal”). The emission of the light caused a photovoltaic signal which triggered a digital storage device that captured and stored the amplified signal as a function of time. The time resolution of the detector plus circuitry was about 1 $\mu$s, which was adequate for the range of signal duration that were observed. The onset of luminescence was well correlated with the onset of cracking, as evidenced by rise in resistance between electrical contacts on either side of the specimen.

Figs.2 to 6 shows the ML intensity versus time plot obtained during cleavage of Ge, Si, Ge$_{0.2}$Si$_{0.8}$, InP, and GaAs crystals, from the result reported by Hanemann and McAlpine [1], Li et al. [2, 3, 7]. It is evident that the rise of ML follows the linear relation between $I$ and $t$.

Figs.7 and 8 shows the plot of ln $I$ versus $(t - t_m)$ curve of Ge, Si, Ge$_{0.2}$Si$_{0.8}$, InP, and GaAs crystals cleaved in vacuum. It is evident that the plots are straight line with a negative slope, which supports Eqs. (29), (30) and (31).

The values of the slope $m$ are determined and they are shown in Table 1 for different semiconductors. It is to be noted that the values of $m$ correspond to that of the C type signals $m$. Table 2 gives the summery of signal types emitting from different crystals. Table 3 gives the density of photons emitted during the cleavage of different crystals.

Thus, it seems that there is a good agreement between the theoretical and experimental result.
Figure 2: Cleavage luminescence from Si single crystal 5mm wide by 0.53 mm thick, cleaved at 1×10⁻⁴ torr, showing new sharp C signal. In (a) we show the change in resistance $R_{CD}$ of the specimen during the cleavage, demonstrating good correlation of luminescence onset with occurrence of crack specimen cleaved by pulling apart (after ref. [2]).

Figure 3: Luminescence signal from Ge crystals, 10mm wide by 0.4 mm thick, observed with Si detector. No optical filters were used, cleaved in air. There are two sharp signals (C) from two crack events, i.e., an additional, separate crack occurred after the first one (after ref. [3]).

Figure 4: Luminescence signal from Ge₀.₂Si₀.₈, 15mm wide by 0.74mm thick, observed on Si detector through 1.32-1.46 eV filter cleaved in vacuum of 5×10⁻⁵ torr (after ref. [3]).

Figure 5: Cleavage luminescence from InP crystal, 4mm wide and 0.39 mm thick, observed on Si detector through optical filter of energy band pass 1.85-2.28 eV cleaved at 4×10⁻⁵ torr. In this the actual output voltages after amplification are given, including on offset voltage that was chosen to suit the particular signal. The time scale commences at a small interval prior to the time of commencement of cleavage (after ref. [3]).
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Figure 6: Cleavage luminescence found from 0.64 mm thick GaAs cleaved by block cleaver at 2×10⁻⁴ torr (after ref. [3]).

Figure 7: Plot of ln I versus (t− tₘ) for Ge, InP and Si crystals.

Fig. 8: Plot of ln I versus (t− tₘ) for Ge₀.₂Si₀.₈ and GaAs crystals.

Table 1: Value of m and 1/m for different semiconductor.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Name of Crystal</th>
<th>m (µs⁻¹)</th>
<th>1/m (µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Ge (in air type, 15 µs)</td>
<td>0.29553</td>
<td>4.0728</td>
</tr>
<tr>
<td>2.</td>
<td>InP (Vacuum, 10 µs)</td>
<td>0.43569</td>
<td>2.295</td>
</tr>
<tr>
<td>3.</td>
<td>Si (Vacuum, 15 µs)</td>
<td>0.11433</td>
<td>8.7466</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.03079</td>
<td>32.478</td>
</tr>
<tr>
<td>4.</td>
<td>Ge₀.₂Si₀.₈ (Vacuum, 300-500 µs)</td>
<td>0.01004</td>
<td>99.6</td>
</tr>
<tr>
<td>5.</td>
<td>GaAs (Vacuum)</td>
<td>0.02181</td>
<td>45.8</td>
</tr>
</tbody>
</table>
Table 2: Summary of signal types produced during the cleavage of semiconductors (A refers to band gap energies, B refers to surface state energies and C to defect energies) [2].

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Name of Crystal</th>
<th>Signal</th>
<th>Energy (eV)</th>
<th>Duration (μs)</th>
<th>Ambient Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Si</td>
<td>A</td>
<td>1.1 – 2.7</td>
<td>300</td>
<td>Vacuum</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>0.26 – 0.01</td>
<td>200</td>
<td>Vacuum</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>1.1 – 1.88</td>
<td>15</td>
<td>Vacuum/air</td>
</tr>
<tr>
<td>2.</td>
<td>Ge</td>
<td>A</td>
<td>0.73 – 1.76</td>
<td>400</td>
<td>Vacuum</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>1.1 – 1.30</td>
<td>15</td>
<td>Vacuum/air</td>
</tr>
<tr>
<td>3.</td>
<td>Ge0.2Si0.8</td>
<td>A</td>
<td>0.73 – 1.64</td>
<td>300 – 500</td>
<td>Vacuum</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>1.1 – 1.46</td>
<td>20 – 40</td>
<td>Vacuum/air</td>
</tr>
<tr>
<td>4.</td>
<td>Ge0.3Si0.9</td>
<td>A</td>
<td>0.73 – 1.64</td>
<td>300 – 500</td>
<td>Vacuum</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>1.1 – 1.30</td>
<td>20 – 40</td>
<td>Vacuum/air</td>
</tr>
<tr>
<td>5.</td>
<td>Ge0.7Si0.3</td>
<td>A</td>
<td>0.73 – 1.64</td>
<td>300 – 500</td>
<td>Vacuum</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>1.1 – 1.30</td>
<td>20 – 40</td>
<td>Vacuum/air</td>
</tr>
<tr>
<td>6.</td>
<td>InP</td>
<td>A</td>
<td>1.25 – 0.05</td>
<td>10</td>
<td>Vacuum</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>1.9 – 0.30</td>
<td>10</td>
<td>Vacuum/air</td>
</tr>
</tbody>
</table>

Table 3: Density of photons emitted during cleavage (figure show average value and the range of results in brackets, for the ease of area densities: the number of experiments averaged is N) (I = indirect gap; d = direct gap) [3].

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Name of Crystal</th>
<th>Band gap Energy</th>
<th>Signal type</th>
<th>N</th>
<th>Average density of photons</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Per unit area (cm²) Per unit crack length (cm⁻¹)</td>
</tr>
<tr>
<td>1.</td>
<td>Ge</td>
<td>0.67 (i)</td>
<td>A</td>
<td>8</td>
<td>4(0.2 – 8)×10⁹ 3×10⁸</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>C</td>
<td>5</td>
<td>4(0.2 – 8)×10⁷ 3×10⁷</td>
</tr>
<tr>
<td>2.</td>
<td>Si</td>
<td>1.14 (i)</td>
<td>A</td>
<td>41</td>
<td>1(0.2 – 2)×10¹⁰ 6×10⁸</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>B</td>
<td>9</td>
<td>9(0.5 – 30)×10¹¹ 9×10⁸</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>C</td>
<td>26</td>
<td>26(1 – 6)×10⁸ 2×10⁷</td>
</tr>
<tr>
<td>3.</td>
<td>InP</td>
<td>1.35 (d)</td>
<td>A</td>
<td>13</td>
<td>1(0.3 – 2)×10⁸ 4×10⁸</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>C</td>
<td>14</td>
<td>6(3 – 9)×10⁷ 3×10⁸</td>
</tr>
<tr>
<td>4.</td>
<td>GaAs</td>
<td>1.43 (d)</td>
<td>A</td>
<td>14</td>
<td>4(2 – 12)×10⁵ 3×10¹⁴</td>
</tr>
</tbody>
</table>

Conclusions
The important conclusion drawn from the studies on the cleavage-induced ML of elemental and III–V semiconductors are given below:
(i) The formation of crack-induced localized states is responsible for the ML excitation produced during the cleavage of elemental and III–V semiconductors. According to this mechanism, as the atoms are drawn away from each other in advancing crack tip, the decreasing wave-function overlap across the crack may result in localized states which are associated with increasing electron energy. If the energy of these localized states approaches that of the conduction band via tunneling would be possible, creating minority carriers, and consequently the electron hole recombination may give rise to the mechanoluminescence. The de-excitation of electrons excited by cleavage in to conduction band, shallow traps, into upper surface states and defect centres, produce the light having different wave lengths.

(ii) When an elemental or III–V semiconductor is cleaved, initially the ML intensity increases with time, attains a peak value $I_m$ at the time $t_m$ corresponding to completion of the cleavage and then it decreases exponentially with time, in which the decay time of ML depends on the type of signal emitted such as type A, B or C.

(iii) Three types of signal, namely A, B and C, and produced during the cleavage of elemental and III–V semiconductors. Type A signals arises due to the cleavage induces population of the bulk conduction band and shallow traps and their subsequent de-excitation. Type B signal produced due to the cleavage induced population of the surfaces states and their subsequent de-excitation, and type C signals occurs due to the cleavage induced population of the defect centres and their subsequent de-excitation.

(iv) The peak ML intensity $I_m$ and the total ML intensity $I_T$ increase directly with the area of the newly created surfaces of crystals.

(v) The wavelength of the light induced by cleavage of elemental and III–V semiconductors lies in the infrared region.

(vi) From the measurement of the ML , band gap of the material, energy of the surface states, energy of the defect states, life time of the electrons in shallow traps, life time of electrons in the surface states, lifetime of electrons in defect centres and the velocity of the crack propagation in the materials can be determined.

$$v = \frac{H}{t_m}$$

(vii) The expression derived for the ML of elemental and III–V semiconductors are as given below

$$I_1 = 2\eta_1 Z_1 Wv[1 - \exp(-\phi_1 t)]$$
$$I_2 = 2\eta_2 Z_2 Wv[1 - \exp(-\phi_2 t)]$$
$$I_3 = \eta_3 Z_3 Wv[1 - \exp(-\phi_3 t)]$$
$$I_{1r} = 2\eta_1 Z_1 Wv\phi_1 t$$
$$I_{2r} = 2\eta_2 Z_2 Wv\phi_2 t$$
$$I_{3r} = 2\eta_3 Z_3 Wv\phi_3 t$$
\[ I_m = (n_1 \phi_1 Z_1 + n_2 \phi_2 Z_2 + n_3 \phi_3 Z_3) \]
\[ I_T = [n_1 Z_1 + n_2 Z_2 + n_3 Z_3] A \]
\[ I_{1d} = n_i g_i \phi_1 t_m \exp(-\phi_1(t-t_m)) \]
\[ I_{2d} = n_2 g_2 \phi_2 t_m \exp(-\phi_2(t-t_m)) \]
\[ I_{3d} = n_3 g_3 \phi_3 t_m \exp(-\phi_3(t-t_m)) \]

and, \( t_m = \frac{H}{v} \)

References