Cleavage mechanoluminescence in elemental and III–V semiconductors


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Abstract

The present paper reports the theory of mechanoluminescence (ML) produced during cleavage of elemental and III–V semiconductors. It seems that 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 an advancing crack tip, the decreasing wave function overlap across the crack may result in localized states which is associated with increasing electron energy. If the energy of these localized states approach that of the conduction band, transition to the conduction band via tunnelling would be possible, creating minority carriers, and consequently the electron–hole recombination may give rise to mechanoluminescence. 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 of the semiconductor, and then it decreases following power law decay. Expressions are derived for the ML intensity \( I_m \) corresponding to the peak of the ML intensity versus time curve and for the total ML intensity \( I_T \). It is shown that both \( I_m \) and \( I_T \) should increase directly with the area of the newly created surfaces of the crystals. From the measurements of the ML intensity, the velocity of crack propagation in material can be determined by using the relation \( v = H/t_m \).

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1. Introduction

Mechanoluminescence (ML) is a type of luminescence produced during the mechanical deformation of solids. It can be excited either by grinding, rubbing, cutting, cleaving, shaking, scratching, compressing, or by crushing of solids. ML can also be excited by thermal shocks caused by drastic cooling or heating of materials or by the shock waves produced during exposure of samples to powerful laser pulses. ML also appears during the deformation caused by the phase transition or growth of certain crystals. ML also occurs during separation of two dissimilar materials in contact.

Jenny [1] was first to report the ML of elemental and III–V semiconductors. He has found that the energy of the emitted photons increases with the band gap of the materials and both the n- and
p-type semiconductors of the same material exhibit similar spectra. Haneman and McAlpine [2] have studied cleavage luminescence from silicon. They report direct detection of light emission from single crystal silicon cleaved in vacuum. The emission occurs in at least in two wavelength regions and above 1 eV energy (A) and the other between 0.25 and 0.36 eV (B). Intensities for about 0.1 cm² cleaved areas are in the region of $10^{12}$ photons in region A and $10^{11}$ photons in region B. The B radiation is of significantly longer duration than the A radiation. The latter can be explained by radiative bulk bond recombination, and the B radiation by radiative surface band recombination. The duration of the B radiation shows that the surface state gap is indirect.

Li et al. [3] have studied the cleavage luminescence from GaAs and InP as well as from Si in high vacuum. A new Si signal has been found, tentatively ascribed to surface defect. Unlike Si, the III–V materials also show luminescence from cleavage in air. The results are explained in terms of the presence of a dip in the potential barrier at the clean surface due to wave function penetration. This is appreciable for Si but not for GaAs or InP. They have shown that the radiation energy during the cleaving of the crystal in high vacuum is $0.26 \pm 0.01$ eV range [4]. Li et al. [5] have reported the cleavage luminescence from InP, Ge and three different compositions of Ge$_x$Si$_{1-x}$. They have found that all compounds have common characteristic in that there are at least two types of emission in different wavelength regions. One type appears from cleavage in vacuum only and has relatively long durations in the cases of the elemental semiconductors. The origin of luminescence is recombination of cleavage-excited electrons across the bulk band gap. There is evidence that the excited electrons are in a non-equilibrium (“hot”) distribution. The other type of luminescence appears also in air and has short (20 μs or less) durations for all of the materials. This radiation is ascribed to recombination at surface defect, including vacancies.

The present paper reports the theory of ML produced during the cleavage of elemental and III–VI group semiconductors, and makes a comparison between the experimental and theoretical results.

2. Mechanisms of ML in elemental and III–V semiconductors

To date, the mechanisms of ML in elemental and III–V semiconductors have not been studied in detail. For the ML excitation in elemental and III–V semiconductors, the following models may be proposed: (i) charging of newly creates surfaces, (ii) thermal generation of charge carriers, (iii) recombination of fracture-generated defects, and (iv) formation of crack-induced localized states. In the following paragraphs, we would discuss the suitability of these models.

2.1. Charging of newly created surfaces

Since Ge, Si, InP and GaAs are centrosymmetric, charging of newly created surfaces may not take place due to the piezoelectrification. As these semiconductors have covalent bonding, the charging of newly creates surfaces may not take place due to the baro-diffusion of charged ions near the tip of the moving cracks. It is to be noted that the defects takes place owing to difference of pressure (baro) between two newly created surfaces near the crack tip [6]. There may be the possibility of charging of newly created surfaces due to the movement of charged dislocations, but it may also be ruled out in the following way. At the core of dislocations in semiconductors such as Ge or Si there are electrons states associated with dangling bonds, and these may act as donors or as acceptors. In general, the dislocation will be charged to such an extent that the potential at the core brings these states to about the same energy as the Fermi level. The dislocation will be surrounded by a charge cloud in which there is an appropriate excess or deficiency of electrons or holes to compensate the line charge. The properties of these charged dislocation have been studied both theoretically and experimentally [7–9]. No electrical effects of the movements of dislocation in a semiconductors like Ge, Si, InP and GaAs can be detected, because the screening charge moves with
the dislocation very easily [10]. Thus, the ML model involving surface charging of newly created surfaces may not provide a dominating process for the ML in elemental and III–V semiconductors.

2.2. Thermal generation of charge carriers

Thermal generation of charge carriers during fracture could also explain the transients [11]. Thermal generation of electron–hole pairs by excitation across the band gap would require temperature in excess of 700 K to produce the observed electronic transitions, if we assume that 1 nm on each side of the crack tip was heated during fracture. This heating could be the result of irreversible process in the region of the crack tip. Although the fracture of Si and other semiconductors is generally not associated with macroscopic plastic deformation [12], surfaces, relaxation behind the crack tip may yield significant energies. For Si, the energy of the relaxed surface is about 0.36 eV per surface atom lower than that of the ideal truncated bulk [13]. Some of this energy may be available for surface heating as seems to be the case for various glasses. Rough measurements of the temperature rise during the fracture of glass and quartz have yielded values in excess of 2000 K [14]. The intensity and duration of the thermal pulse is limited by conductive cooling. The high thermal diffusivity of Si relative to glass suggests that the temperature rise in Si is much less than in glasses. However, rapid crack growth would be associated with rapid heating and higher final temperature, and thus higher carrier concentrations.

The total number of photons produced during the creation of unit surface area of Ge, Si and GaAs are $3 \times 10^8$, $1.52 \times 10^{10}$ and $3 \times 10^4$, respectively [5]. The thermal conductivity of Ge, Si and GaAs are 0.64, 1.45 and 0.46 W/cm°C, respectively. Since GaAs is a direct band gap semiconductor, and it has low value of thermal conductivity, it should show more ML as compared to Ge and Si which are indirect band semiconductors and have comparatively high value of thermal conductivity. Practically Ge and Si show high ML as compared to GaAs. Therefore, the model involving thermal generation of charge carriers may not provide a dominating process for the ML produced during fracture of elemental and III–V semiconductors.

2.3. Recombination of fracture-generated defects

Other energetic processes occur on fracture surfaces including the production of defects such as vacancies and atoms [15]. The density of such defects is expected to be a strong function of crack velocity and fracture mode. Recombination reactions involving these species could lead to the creation of charge carriers similar to the creation of free electrons during chemisorption of reaction gases on some surfaces [16].

The ML in III–V semiconductors disappears very rapidly after their fracture; however, in the case of Si and Ge the cleavage times are usually much less than the luminescence in the materials [17]. This is visually demonstrated by Busch and Haneman [18], where the luminescence from Si is imaged well after cleavage has completed. However, this does not affect the theory of the present investigation since the recombination times are presented by parameters which are not quantified. The recombination of fracture generated defects is slow process, and if this model is responsible, the ML should appear for a significant time after the cleavage of semiconductors. But it has been found that the ML in semiconductors disappears very rapidly after their fracture. Thus, the ML model involving recombination of fracture generated defects may not be a dominating process in elemental and III–V semiconductors.

2.4. Formation of crack-induced localized states

As the atoms are drawn away from each other in an advancing crack tip, the decreasing wave-function overlap across the crack may result in localized states. Anderson localization is expected to result from variations in crack width and from mismatch across the crack due to shear displacements [11]. Decreasing wave-function overlap is generally associated with increasing electron energy. If the energy of these localized states approach that of the conduction band, transition
to the conduction band via tunnelling would be possible, creating minority carriers. These transitions may be further facilitated by shifts in the conduction band energy due to high stress fields near the crack tip. Subsequently, the radiative recombination of electron and holes may give rise to the mechanoluminescence.

Lemke and Haneman [19] have identified localized states which they associate with wave-function overlap across narrow indentation cracks in Si [16]. Their electron–spin resonance measurements indicate 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 excitations.

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 valence band holes and thus increases the probability of transitions 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 number of photons produced during the creation of unit surface area are $3 \times 10^8$, $1.52 \times 10^{10}$, $7 \times 10^6$ and $3 \times 10^4$ for Ge, Si, InP and GaAs semiconductors, respectively [5]. The band gaps of Ge, Si, InP and GaAs are 0.67, 1.14, 1.35 and 1.43 eV, respectively. Except Ge, it follows that the number of photons emitted decreases with increasing energy of the 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 be due to the low value of the efficiency of radiative transition in this crystal.

### 3. Theory

Strube and Linke [20] have measured the time-resolved crack velocity during the cleavage of alkali halide crystals. They have shown that initially the crack moves at low velocity, but very soon it attains a fixed velocity after attaining a certain crack length. If a crystal having length $L$, breadth $W$ and thickness $H$ is cleaved along the plane parallel to the breadth side, the rate of creation of new surfaces is given by $2Wv$, where $v$ is the average velocity of the separation of cleavage plane or, in other words, the velocity of crack propagation. If $B$ is the number of free charge carriers produced during the creation of unit surface area, then the rate of generation of the charge carriers may be expressed as

$$g = 2BWv.$$  \hfill (1)

In intrinsic semiconductors the number of electrons is equal to number of holes. In this case, luminescence is produced during the radiative recombination of holes and electrons. Hence, the recombination rate is proportional to the square of number of carriers, i.e. $n^2$. This process can be understood involving generation and recombination of carriers. If $z_1$ and $z_2$ are the recombination coefficient for radiative and non-radiative transitions, then the rate equation may be written as

$$\frac{dn}{dt} = g - z_1n^2 - z_2n^2$$

or

$$\frac{dn}{dt} = g - zn^2,$$  \hfill (2)

where $z = (z_1 + z_2)$, and $n$ is the number of carriers in the respective band at any time $t$ or

$$\frac{dn}{g - zn^2} = dt.$$  \hfill (3)

For $n = 0$, at $t = 0$, the integration of Eq. (3) gives

$$n = \sqrt{g/z} \tanh (t\sqrt{gz}).$$  \hfill (4)
3.1. Case I: rise of ML intensity

The rise of intensity of bimolecular ML may be given by

\[ I_t = x_1 n^2 = \frac{x_1 g}{\alpha} \tanh^2 t \sqrt{g \alpha} \] (5)

or

\[ I_t = \frac{x_1 g}{\alpha} \left[ \frac{\exp(t \sqrt{g \alpha}) - \exp(-t \sqrt{g \alpha})}{\exp(t \sqrt{g \alpha}) + \exp(-t \sqrt{g \alpha})} \right]^2. \] (6)

For small values of \( t \), Eq. (6) may be written as

\[ I_t = \frac{x_1 g}{\alpha} \left[ \frac{1 + (t \sqrt{g \alpha}) - 1 + \sqrt{g \alpha}}{1 + (t \sqrt{g \alpha}) + 1 - (t \sqrt{g \alpha})} \right]^2 \]

or

\[ I_t = \frac{x_1 g}{\alpha} \left[ \frac{2t \sqrt{g \alpha}}{2} \right]^2 \]

or

\[ I_t = x_1 g^2 t^2. \] (7)

Eq. (7) indicates that \( I_t \) should increase quadratically with \( t \).

Eq. (5) shows that when a semiconductor material is cleaved, initially, the ML intensity should increase linearly with time (\( t \)) and finally it should attain a saturation value \( I_{rs} \) given by the equation

\[ I_{rs} = \frac{x_1 g}{x_1 + x_2} \]

or

\[ I_{rs} = \frac{2x_1}{x_1 + x_2} BW v. \] (8)

3.2. Case II: decay of ML intensity

When the light source will be switched off, the rate of generation \( g \), of carriers will become zero and Eq. (2) may be expressed as

\[ \frac{dn}{dt} = -2n^2. \] (9)

If the cleavage is completed at \( t = t_m \), then taking \( n = \sqrt{g/\alpha} \), at \( t = t_m \), and we get

\[ n = \sqrt{g/\alpha} \frac{1}{(\sqrt{g \alpha})(t - t_m) + 1}. \] (10)

Thus, the decay of ML intensity may be given by

\[ I_d = x_1 n^2 = \frac{x_1 g}{\alpha} \left[ \frac{1}{(\sqrt{g \alpha})(t - t_m) + 1} \right]^2. \] (11)

For \( \sqrt{g \alpha}(t - t_m) > 1 \), we get

\[ I_d = \frac{x_1 g}{\alpha g \alpha (t - t_m)^2} \]

or

\[ I_d = \frac{x_1}{\alpha^2 (t - t_m)^2}. \] (12)

The above equation shows that the decay of ML intensity should follow the power law.

For \( t = t_m \) using Eq. (11), the maximum ML intensity may be expressed as

\[ I_m = \frac{x_1 g}{\alpha} = \frac{2x_1 BW v}{\alpha}. \] (13)

From Eqs. (11) and (13), we get

\[ \frac{I_m}{I_d} = \left[ (\sqrt{g \alpha})(t - t_m) + 1 \right]^2 \]

or

\[ \frac{I_m}{I_d} \left( \frac{I_m}{I_d} - 1 \right) = \sqrt{g \alpha}(t - t_m) \]

or

\[ \left( \frac{I_m}{I_d} - 1 \right) = \sqrt{2BW v \alpha}(t - t_m). \] (14)

Eq. (14) indicates that the plot between \( \left( \sqrt{I_m/I_d} - 1 \right) \) and \( (t - t_m) \) should be a straight line, in which the slope should be equal to \( \sqrt{2BW v \alpha} \).
3.3. Total ML intensity

The total ML intensity may be given by the area below the ML intensity versus time curve, and it may be expressed as

\[
I_T = \int_0^{t_m} \frac{\alpha_1 g}{\alpha} \tanh^2 t \sqrt{g \alpha} \, dt + \int_{t_c}^{t_m} \frac{\alpha_1 g}{\alpha} \frac{dt}{\sqrt{g \alpha(t - t_c) + 1}}. \tag{15}
\]

Integrating Eq. (15), we get

\[
I_T = \frac{\alpha_1 g^{1/2} t_m \sqrt{g \alpha} - \tanh t_m \sqrt{g \alpha} + 1}{\alpha}. \tag{16}
\]

For \( t_m \sqrt{g \alpha} > 1 \), \( \tanh(t_m \sqrt{g \alpha}) = 1 \), thus Eq. (16) may be expressed as

\[
I_T = \frac{\alpha_1 g t_m}{\alpha}
\]

or

\[
I_T = \frac{2\alpha_1 BW \sqrt{t_m}}{\alpha}
\]

or

\[
I_T = \frac{2\alpha_1 BWH}{\alpha}
\]

or

\[
I_T = \frac{\alpha_1 BA}{\alpha}, \tag{17}
\]

where \( A \) is the area of newly created surfaces.

4. Experimental support to the proposed theory

In the past, detailed measurements have been made on the ML produced during cleavage of semiconductors [2–4]. 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 on a few mm above the crack. For bending, the specimen was clamped tightly between steel or aluminium blocks. For uniaxial tension, they were held by a vacuum epoxy (“Torr seal”). The emission of 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. 1 and 2 show the block diagrams of the devices used for the ML measurements.

Figs. 3–7 show the ML intensity versus time plot obtained during cleavage of Si, Ge, Ge\(_{0.2}\)Si\(_{0.8}\), INP and GaAs crystals. From the results reported by Haneman and McAlpine [2] and Li et al. [3–5], it is evident that the rise of ML follows the quadratic relation between \( I_c \) and \( t \), but some smaller crystals this is not apparent. During the fracture of Si crystals, Langford et al. [17] have found a non-linear increase of the current with time.
Fig. 8 shows the plot of $\sqrt{t_m/t_d - 1}$ versus $(t - t_m)$ curve for Si, Ge, Ge$_{0.2}$Si$_{0.8}$, InP and GaAs crystals cleaved in vacuum. It is evident that this plot is a straight line with a positive slope, which supports Eq. (14). The value of slope should be $\sqrt{\gamma g}$, which is shown in Table 1 or different semiconductors.

Table 2 gives the summary of signal types emitted from different crystals. Table 3 gives the density of photons emitted during the cleavage of different crystals.

Fig. 9 gives the schematic diagram showing origins of luminescence due to de-excitation of
electron excited by cleavage into bulk conduction band (A), into upper surface states (B), and recombination at defects (C).

5. Conclusions

The important conclusions drawn from the present investigations are as given below:

(i) The mechanism related to 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 an advancing crack tip, the decreasing wavefunction overlap across the crack may result in localized states which is associated with increasing electron energy. If the energy of these localized states approaches that of the conduction band, transition to the conduction band via tunnelling would be possible, creating minority carriers, and consequently

Fig. 6. Cleavage luminescence from InP crystal, 4 mm wide and 0.39 mm thick, $\sqrt{I_m/I_d} = 1$ observed on Si detector through optical filter of energy band pass 1.85–2.28 eV cleaved at $4 \times 10^{-4}$ Torr. In this the actual output voltage after amplification are given, including an 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 Li et al. [5]).

Fig. 7. Cleavage luminescence found from 0.64 mm thick GaAs cleaved by block cleaver at $2 \times 10^{-4}$ Torr (after Li et al. [3]).
Fig. 8. Plot of $\sqrt{t_m/I_d} - 1$ versus $(t - t_m)$ curve for Si, Ge, Ge$_{0.2}$Si$_{0.8}$, InP and GaAs crystals cleaved in vacuum.

Table 1
Value of $t_m$ and $\sqrt{ag}$ for different semiconductors

<table>
<thead>
<tr>
<th>Sl. no.</th>
<th>Name of crystal</th>
<th>Size of crystal</th>
<th>$T_m$ ($\mu$s)</th>
<th>$\sqrt{ag}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ge</td>
<td>10 mm wide and 0.4 mm thick</td>
<td>115</td>
<td>$115.3 \times 10^3$</td>
</tr>
<tr>
<td>2</td>
<td>Si</td>
<td>0.5 mm wide and 0.52 mm thick</td>
<td>120</td>
<td>$16.3 \times 10^3$</td>
</tr>
<tr>
<td>3</td>
<td>Ge$<em>{0.2}$Si$</em>{0.8}$</td>
<td>15 mm wide and 0.74 mm thick</td>
<td>250</td>
<td>$2.98 \times 10^3$</td>
</tr>
<tr>
<td>4</td>
<td>InP</td>
<td>09 mm wide and 0.35 mm thick</td>
<td>117</td>
<td>$134.6 \times 10^3$</td>
</tr>
<tr>
<td>5</td>
<td>GaAs</td>
<td>0.64 mm thick and thickness</td>
<td>125</td>
<td>$7.50 \times 10^3$</td>
</tr>
</tbody>
</table>

Table 2
Summary of signal types produced during cleavage of semiconductors

<table>
<thead>
<tr>
<th>Sl. no.</th>
<th>Name of crystal</th>
<th>Signals</th>
<th>Energy (eV)</th>
<th>Duration ($\mu$s)</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>2</td>
<td>Ge</td>
<td>A</td>
<td>1.1–1.88</td>
<td>15</td>
<td>Vacuum/air</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>0.73–1.46</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>Ge$<em>{0.2}$Si$</em>{0.8}$</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>Ge$<em>{0.3}$Si$</em>{0.9}$</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>1.1–1.46</td>
<td>20–40</td>
<td>Vacuum/air</td>
</tr>
<tr>
<td>5</td>
<td>Ge$<em>{0.7}$Si$</em>{0.3}$</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>

A refers to band gap energies, B to surface state energies and C to defect energies [5].
The electron hole recombination may give rise to mechanoluminescence.

(ii) When an elemental or III–V semiconductors 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 fracture of the semiconductor, and then it decreases following power law decay.

(iii) The intensity $I_m$ corresponding to the peak of the ML intensity versus time curve and the total ML intensity may be expressed by the relations

$$I_m = \frac{2x_1 BWv}{x}, \quad \text{and} \quad I_T = \frac{x_1 BA}{x}.$$  

It is evident that $I_m$ should depend linearly on the width of the crystals, however $I_T$ should increase directly with the area of newly created surfaces crystals.

(iv) From the measurement of the ML intensity, the velocity of crack propagation in a material can be determined by using the relation $v = H/t_m$.


densities emitted during cleavage

<table>
<thead>
<tr>
<th>Sl. no.</th>
<th>Name of crystal</th>
<th>Band gap energy (eV)</th>
<th>Signal type</th>
<th>$N$</th>
<th>Average density of photons</th>
<th>Per unit area (cm$^{-2}$)</th>
<th>Per unit crack-length (cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Ge</td>
<td>0.67</td>
<td>A</td>
<td>8</td>
<td>$4 \times 10^8$</td>
<td>$4 \times 10^7$</td>
<td>$3 \times 10^6$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>C</td>
<td>5</td>
<td>$4 \times 10^7$</td>
<td>$3 \times 10^6$</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>Si</td>
<td>1.14</td>
<td>A</td>
<td>41</td>
<td>$1 \times 10^9$</td>
<td>$6 \times 10^6$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(i) B</td>
<td>9</td>
<td>$9 \times 10^7$</td>
<td>$9 \times 10^6$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>C</td>
<td>26</td>
<td>$2 \times 10^7$</td>
<td>$2 \times 10^6$</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>InP</td>
<td>1.35</td>
<td>A</td>
<td>13</td>
<td>$1 \times 10^8$</td>
<td>$4 \times 10^6$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(d) C</td>
<td>14</td>
<td>$6 \times 10^7$</td>
<td>$3 \times 10^6$</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>GaAs</td>
<td>1.43</td>
<td>A</td>
<td>14</td>
<td>$4 \times 10^5$</td>
<td>$3 \times 10^4$</td>
<td></td>
</tr>
</tbody>
</table>

Figure shows average values and the range of results in brackets. For the case of area densities, the number of experiments averaged in $N$ (i = indirect gap; d = direct gap) [5].

Fig. 9. 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 Li et al. [3]).