Lecture 9

Photogeneration, Absorption, and Nonequilibrium

Reading:

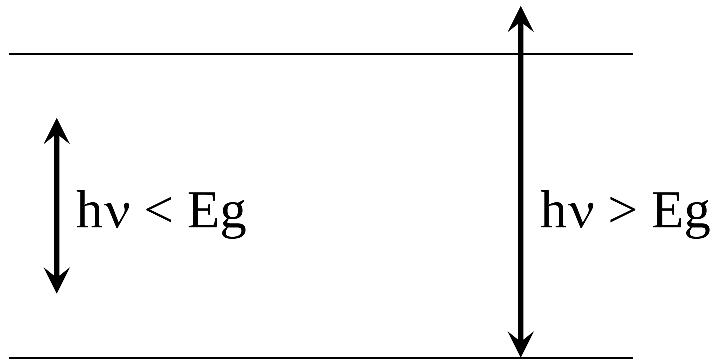
Pierret 3.3-3.4

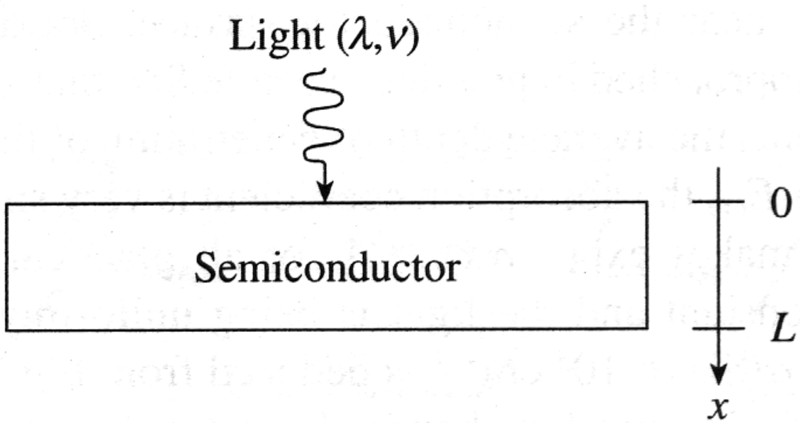
Photogeneration

Light with photon energy, $h\nu < E_g$ is not easily absorbed. A convenient expression for the energy of light is $E=1.24/\lambda$ where λ is the wavelength of the light in um.

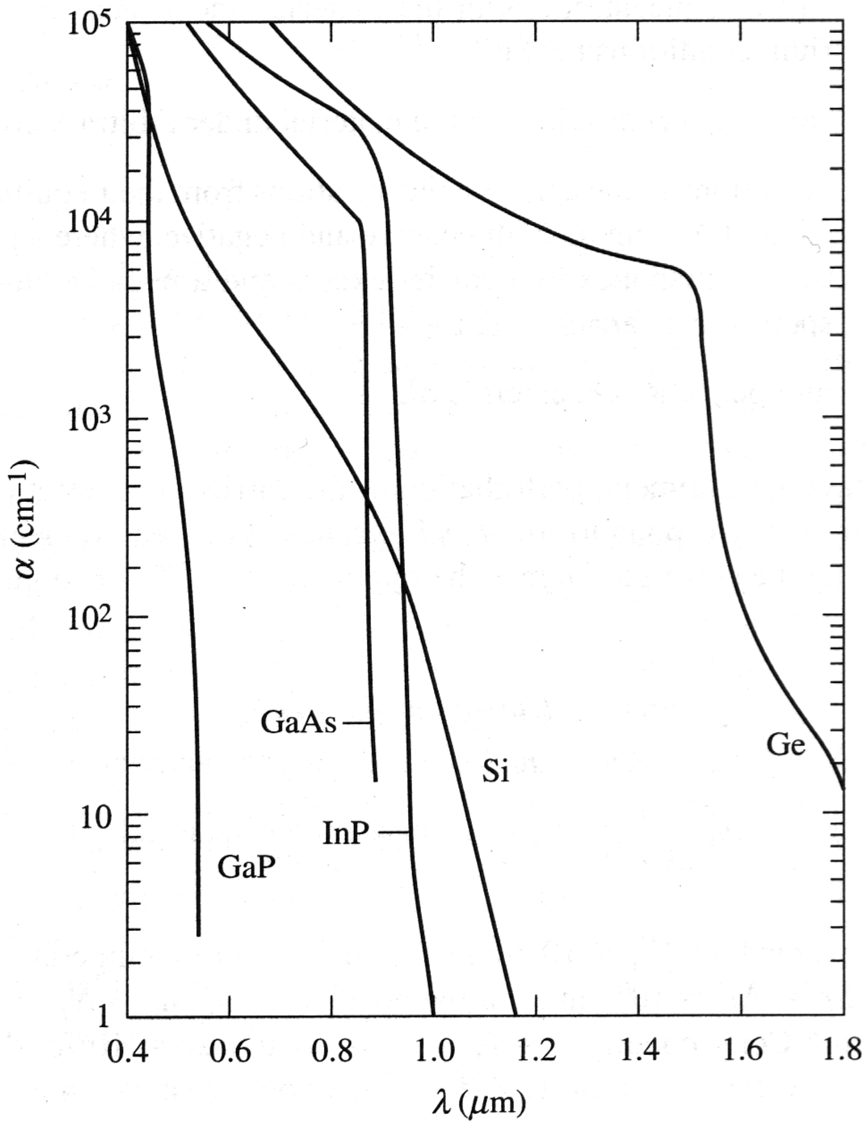
Light with energy, $h\nu > E_g$ is absorbed with the "unabsorbed" light intensity as a function of depth into the semiconductor is $I(x) = I_o e^{-\alpha x}$

> where Io is the initial light intensity, x is distance and α is the absorption coefficient [1/cm].





Photogeneration



Photogeneration

Each Photon with energy greater than Eg can result in one electron hole pair. Thus, we can say,

$$\left.\frac{\partial n}{\partial t}\right|_{Light} = \left.\frac{\partial p}{\partial t}\right|_{Light} = G_L(x,\lambda) \quad where\ G_L(x,\lambda) = G_{LO}e^{-\alpha x} \quad \#/\left(cm^3 - Sec\right)$$

If α is small (near bandgap light), the generation profile can be approximately constant.

If α is large (light with energy>> bandgap), the generation profile can be approximated as at the surface.

Important Nomenclature

n_0, p_0	. . .	carrier concentrations in the material under analysis when equilibrium conditions prevail.
n, p	. . .	carrier concentrations in the material under arbitrary conditions.
$\Delta n \equiv n - n_0$ $\Delta p \equiv p - p_0$	. . .	deviations in the carrier concentrations from their equilibrium values. Δn and Δp can be both positive and negative, where a positive deviation corresponds to a carrier excess and a negative deviation corresponds to a carrier deficit.
N_T	. . .	number of R–G centers/cm^3.

$$n = \Delta n + n_o \text{ and } p = \Delta p + p_o$$

In Non-equilibrium, np does not equal n_i^2

Low Level Injection

$\Delta p = \Delta n << n_o$ and $n \sim n_o$ in n-type material

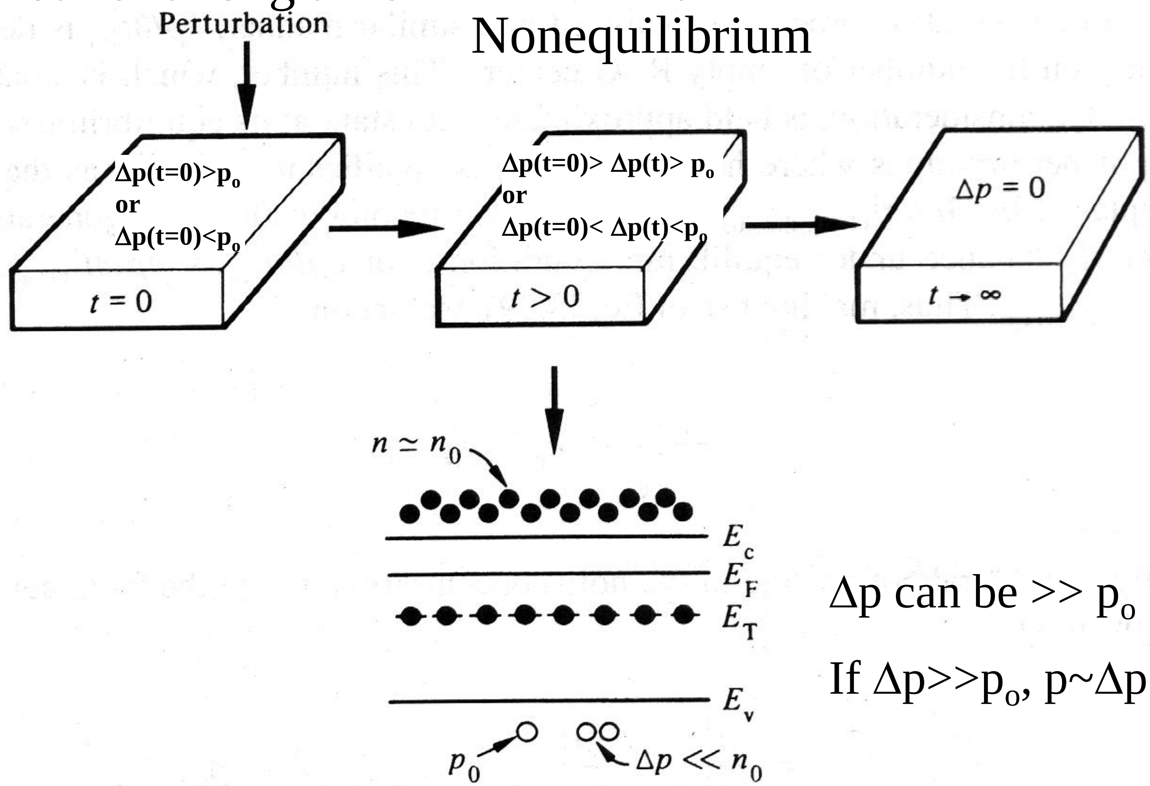
$\Delta p = \Delta n << p_o$ and $p \sim p_o$ in p-type material

Carrier Concentrations after a “Perturbation”

Steady State if perturbation has been applied for a long time

Non-Steady State, Nonequilibrium

Equilibrium



Δp can be >> p_o

If $\Delta p \gg p_o$, $p \sim \Delta p$

After the carrier concentrations are perturbed by some stimulus (leftmost case) and the stimulus is removed (center case) the material relaxes back toward it’s equilibrium carrier concentrations.

Material Response to “Non-Equilibrium”: Relaxation Concept

Consider a case when the hole concentration in an n-type sample is not in equilibrium, i.e., pn does NOT equal n_i^2

$$\left.\frac{\partial p}{\partial t}\right|_{thermal\quad R-G} = -\frac{\Delta p}{\tau_p} \qquad where \quad \tau_p = \frac{1}{c_p N_T}$$

$$where\ \tau_p\ is\ the\ minority\ carrier\ lifetime$$

$$c_p\ is\ a\ proportionality\ constant$$

$$N_T\ is\ the\ "trap"\ concentration$$

- The minority carrier lifetime is the average time a minority carrier can survive in a large ensemble of majority carriers.
- If Δp is negative➔Generation or an increase in carriers with time.
- If Δp is positive➔Recombination or a decrease in carriers with time.
- Either way the system “tries to reach equilibrium”
- The rate of relaxation depends on how far away from equilibrium we are.

Material Response to "Non-Equilibrium": Relaxation Concept

Likewise when the electron concentration in an p-type sample is not in equilibrium, i.e., pn does NOT equal n_i^2

$$\left.\frac{\partial n}{\partial t}\right|_{thermal \quad R-G} = -\frac{\Delta n}{\tau_n} \qquad where \quad \tau_n = \frac{1}{c_n N_T}$$

$$where\ \tau_n\ is\ the\ minority\ carrier\ lifetime$$

$$c_n\ is\ a\ different\ proportionality\ constant$$

$$N_T\ is\ the\ \text{"trap"}\ concentration$$

More generally for any doping case:

$$\left.\frac{\partial n}{\partial t}\right|_{thermal \quad R-G} = \left.\frac{\partial p}{\partial t}\right|_{thermal \quad R-G} = \frac{n_i^2 - np}{\tau_p(n+n_1)+\tau_n(p+p_1)}$$

Same unit as above

$$where...$$

$$n_1 \equiv n_i e^{(E_T - E_i)/kT} \quad and \quad p_1 \equiv n_i e^{(E_i - E_T)/kT}$$

Example: After a long time on, a light is switched off

$$\frac{\partial n}{\partial t} = -\frac{\Delta n}{\tau_n} \qquad \textit{has a solution}$$

$$n(t) = n_o + \underbrace{\Delta n_o e^{-\left(t/\tau_n\right)}}_{\Delta n(t)} \quad \textit{where } \Delta n_o = \textit{initial excess electron concentration}$$

$$\frac{\partial n}{\partial t} = -\frac{\Delta n}{\tau_n}$$

$$\frac{\partial(n_o + \Delta n)}{\partial t} = \frac{\partial(\Delta n)}{\partial t} = -\frac{\Delta n}{\tau_n}$$

$$\Downarrow$$

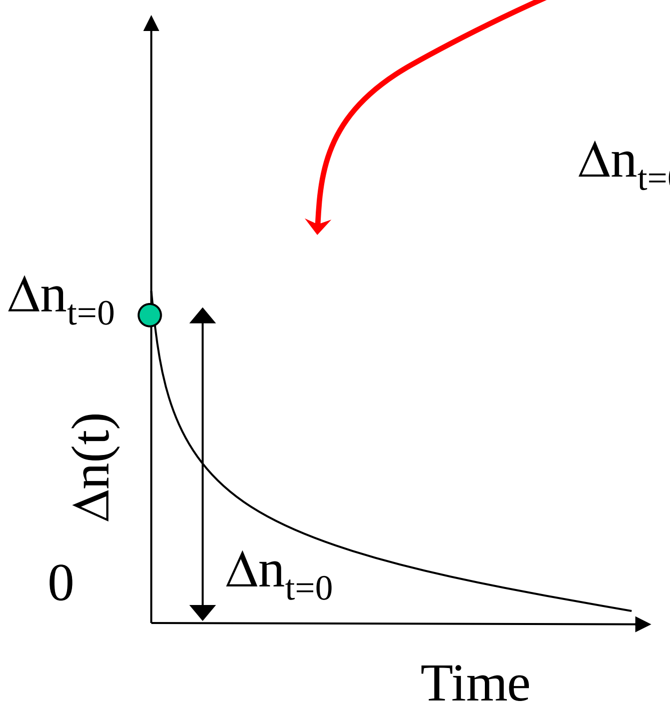
$$\Delta n(t) = A + Be^{-\left(t/\tau_n\right)}$$

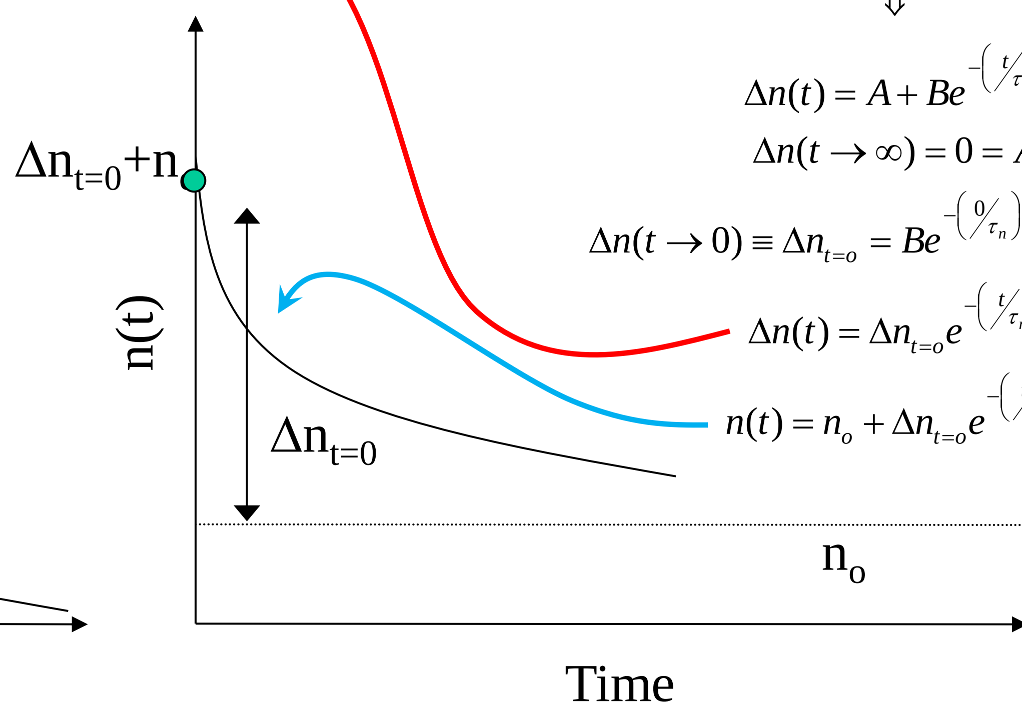
$$\Delta n(t \to \infty) = 0 = A$$

$$\Delta n(t \to 0) \equiv \Delta n_{t=o} = Be^{-\left(0/\tau_n\right)} \Rightarrow \Delta n_o = B$$

$$\Delta n(t) = \Delta n_{t=o} e^{-\left(t/\tau_n\right)}$$

$$n(t) = n_o + \Delta n_{t=o} e^{-\left(t/\tau_n\right)}$$





Material Response to "Non-Equilibrium": Relaxation Concept

Carrier Relaxation can also be achieved through Direct recombination

Given: $\Delta n = \Delta p$, $n = n_o + \Delta n$, $p = p_o + \Delta p$

Low Level Injection ==> $\Delta n << N_a$ and High Level Injection ==> $\Delta n >> N_a$

•Recombination Rate, $R = Bnp$ [#/cm^3 sec.] (depends on number of electrons and holes present)

• In Thermal Equilibrium,

$np = n_i^2$ where n_i^2 is the n-p product due to thermal generation (intrinsic generation)

Recombination rate, $R = B\,n_i^2 = G$, Generation Rate where B is a constant

Under Illumination (Non-thermal equilibrium), np ⑤ n_i^2

Optional

Net Recombination Rate, $-dn/dt = R - G = B(np - n_i^2)$

but, $\Delta n = \Delta p$

$$-dn/dt = B(np - n_i^2)$$
$$= B((n_o + \Delta n)(p_o +.\ \Delta p) - n_i^2)$$
$$= B(\ n_o p_o - n_i^2 + \Delta p n_o + \Delta n p_o + \Delta n \Delta p\ )$$
$$= B\Delta n(\ 0 \qquad + n_o + p_o + \Delta n)$$
$$= B\Delta n(n_o + p_o + \Delta n)$$

Thus, using our lifetime definition,

$$-dn/dt = -\Delta n/\ \tau_e$$
$$\tau_e = 1/(B(n_o + p_o + \Delta n))$$

Material Response to "Non-Equilibrium": Relaxation Concept

Carrier Relaxation can also be achieved through Direct recombination

Special cases:

Low Level Injection: Δn<<majority carrier density

$$\tau_e=1/(B(n_o + p_o))$$

and if the material is n-type:

$$\tau_e=1/(Bn_o)$$

or p-type:

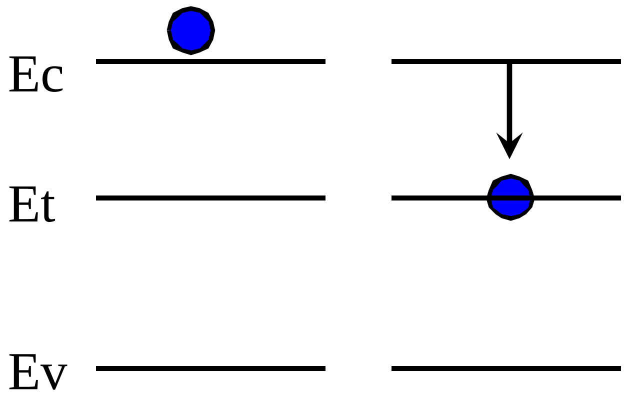
$$\tau_e=1/(Bp_o)$$

Optional

High level injection: Δn>> majority carrier density

$$\tau_e=1/(B\Delta n)$$

Electron Capture and Emission



Electron Capture

How many electrons are available for capture

Number of empty defect sites

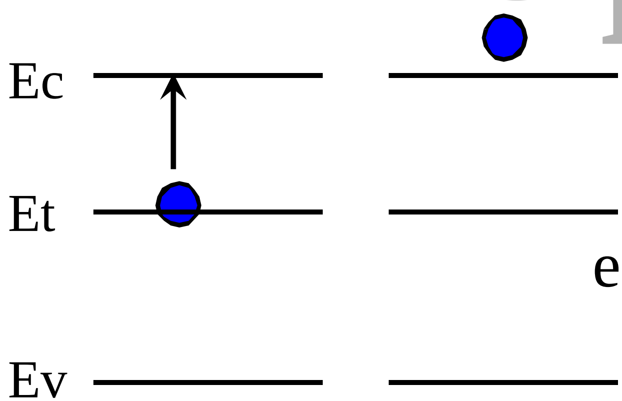
$$c_e = v_{th,e}\, \sigma_n\, n\, N_t\, (1-f(E))$$

Electron Capture Rate

Thermal velocity: How fast the electrons are moving

Capture cross section: Effective size of the defect. Units of area

Optional



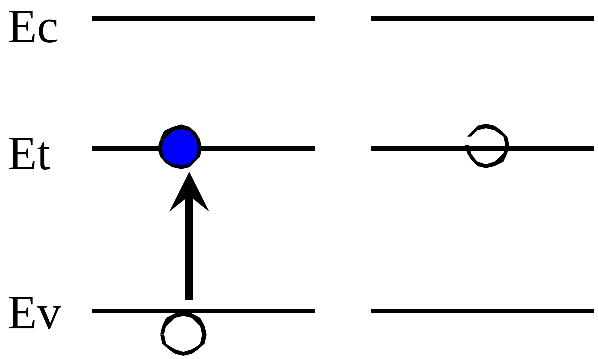
Electron Emission

Number of filled defect sites

$$e_e = e_n\, N_t\, f(E) \quad \text{where } e_n = v_{th,e}\, \sigma_n\, N_c\, e^{-(Ec-Et)/KT}$$

Electron Emission Rate

Hole Capture and Emission



Hole Capture

How many holes are available for capture

Number of filled defect sites

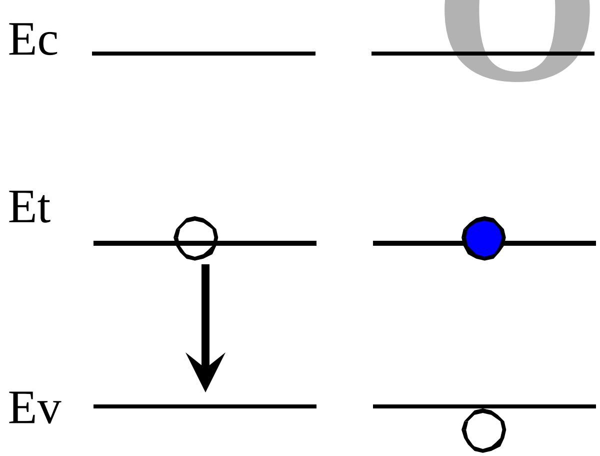
$$c_p = v_{th,p}\,\sigma_p\,p\,N_t\,f(E)$$

Capture cross section: Effective size of the defect. Units of area

Hole Capture Rate

Thermal velocity:How fast the holes are moving

Optional



Hole Emission

Number of empty defect sites

$$e_p = e_h\,N_t\,(1 - f(E))$$

$$\text{where } e_h = v_{th,p}\,\sigma_p\,N_v\,e^{-(Et-Ev)/KT}$$

Hole Emission Rate

Electron and Hole Capture and Emission

Recombination:

electron capture / hole capture

hole capture / electron capture

Generation:

hole emission / electron emission

electron emission / hole emission

Optional

Recycling of carriers into bands:

hole capture / hole emission

electron capture / electron emission

Carrier Concentrations after a "Perturbation"

$$\left.\frac{\partial p}{\partial t}\right|_{Recombination} = -c_p N_T p \quad and \quad \left.\frac{\partial p}{\partial t}\right|_{Generation} = c_p N_T p_o$$

Optional

Plenty of Electrons

E_c

E_f

R-G Center Concentration N_T

E_T

Filled with Electrons

E_v

Very few Holes

Electron and Hole Capture and Emission

In steady state non-equilibrium, the number of electrons and holes are constant:

$$G - (c_e - e_e) = dn/dt = 0$$

$$G - (c_p - e_p) = dp/dt = 0$$

⑧The net recombination/generation rate is,

Optional

This equation can be used to solve for f'(E), the non-equilibrium fermi distribution function (which does NOT equal f(E), then calculated as,