Nitride thin film characterization

- Hall measurement
  - Mobility
  - Sheet carrier density
- Capacitance-voltage measurements (CV)
  - Carrier conc. vs. distance
  - Trap densities
- Deep level transient spectroscopy (DLTS)
  - Deep trap levels
- Atomic force (AFM) and transmission electron microscopy (TEM)
  - Surface and interface studies
- Photoluminescence (PL)
  - Bandgap
  - Purity of material and uniformity
- X-ray diffraction (XRD)
  - Lattice constant and composition
  - Structure and defects
Lorentz force and Hall effect

\[ F = qv \times B \]

\[ = q \frac{J_x}{nq} \times B \]

\[ = q \frac{nq \mu_e E_x}{nq} \times B \]

\[ = qE_y = q \frac{V_H}{w} \]

\[ \mu_e = \frac{V_H}{wE_x B} = \frac{LV_H}{wR_x IB} = \frac{V_H}{BL \rho_{\text{sheet}}} \]

\[ n_{\text{sheet}} = \frac{\sigma_{\text{sheet}}}{q \mu} = \frac{1}{q \rho_{\text{sheet}} \mu} \]

\( \mu \) can be calculated from the knowledge of B and \( V_H \). \( N_{\text{sheet}} \) can be calculated from \( \mu \) if \( \rho_{\text{sheet}} \) is known.
Measurement of Hall voltage and resistivity

Measurement of Resistivity

\[ R_A = \frac{V_{43}}{I_{12}} \]

\[ R_B = \frac{V_{14}}{I_{23}} \]

Measurement of Hall voltage

\[ V_H = V_{24P} \]

\[ F(Q) = 1, \text{ if } R_A = R_B \]

\[ \rho_{\text{sheet}} = \frac{\pi}{2 \ln 2} \left[ \frac{V_{43}}{I_{12}} + \frac{V_{14}}{I_{23}} \right] F(Q) \]

where \( Q = \frac{R_A}{R_B} \)
Summary of the Hall measurement

- For Hall measurements the magnitude of the magnetic field should be small to avoid magneto-resistance or reduction in conductance due to the magnetic field.
- Measurement of both mobility and sheet charge density is possible.
- The volume density of carriers is possible if the thickness of the sample is known.
- The sign of the charge carriers can be found from the sign of the Hall voltage.
- Advantageous for samples having 2DEG since direct measurement of sheet charge density can be made unlike CV technique.
Sources of inaccuracies

- The Hall factor \( r = \langle r^2 \rangle / \langle r \rangle^2 \) which depends on the scattering mechanisms
- The Hall mobility is related to the conductivity mobility as \( \mu_H = r \mu_c \)
- The contacts should be ohmic
- The contact sizes should be as small as possible w.r.t. the distance between them (see Van der Pauw paper)
- A special cloverleaf geometry is used for accurate measurements which is relatively unaffected by the size of the contacts
- Multiple conduction paths, if present, will lead to errors in mobility estimates

Special geometry to reduce the effect of the contact size
Capacitance-Voltage measurements for MOS junctions

- The ac voltage magnitude should be much lower than the dc voltage magnitude
- Typically the ac voltage is ~15 mV rms
- The MOS junction differs from the schottky junction by its ability to create inversion
- The total capacitance is given by the series combination of the oxide capacitance $C_0$ and the depletion capacitance $C_S$
- For MOS capacitance (Si based devices), it is important for measuring trapped charges and oxide thickness, apart from carrier density estimation
High and low frequency CV curves

\[ C = \begin{cases} 
  C_0 & \text{Accum.} \\
  \frac{C_0}{1 + \frac{K_0 W}{K_S x_0}} & \text{Depl.} \\
  C_0 & \text{Inv.} \ (\omega \to 0) \\
  \frac{C_0}{1 + \frac{K_0 W_T}{K_S x_0}} & \text{Inv.} \ (\omega \to \infty) 
\end{cases} \]

Minority carrier concentration cannot respond to high frequency signal since they are generated by thermal excitation.
CV measurements with Schottky contacts

- Large contact is grounded and voltage applied to the small contact
- +ve bias applied for p-type doping and –ve bias applied for n-type doping
- Larger area contact have smaller resistance and less voltage drop

Contacts for CV measurement setup (Mercury probe)

Large area acting as ohmic contact
Small area Schottky contact

-qV_g
L_{dep}
Obtaining CV data for practical samples

\[ N_d(x_d) = -\frac{C^3}{qK_s \varepsilon_0 A^2 \frac{dC}{dV}} \]

The doping concentration (cm\(^{-3}\)) can be obtained from the magnitude of the capacitance and the slope of the C-V curve.

The exact profile of the carrier concentration is not possible to obtain due to carrier spreading.
Problems and limitations of CV (Hg probe)

• Problems with low doping: increased series resistance and significant voltage drop across resistance and change in the phase angle
• Problems with high doping: Lower probing depth limited by tunneling and possible breakdown of the semiconductor material
• Profile obtained does not give the dopant density in presence of a doping gradient due to carrier diffusion
• In presence of deep traps the CV profile measures the net carrier concentration
The Electrochemical CV technique

Widely used in the GaAs industry where $n^+$ doped GaAs layers are very common due to contact formation

- An aqueous solution is used in contact with the semiconductor to act as the schottky junction (e.g. 1,2 dihydroxybenzene-3.5-disulphonic acid disodium salt solution works for GaAs)

- The solution etches the semiconductor continuously (in presence of holes) as the readings are taken, and so very low voltage needs to be applied to deplete the material

- For p-type materials holes are already there, but for n-type material holes have to be generated by super bandgap illumination

- Problems with ECV:
  - Cumbersome
  - The solution can get contaminated easily
**Effects of gradients in doping**

- The CV measurement can only profile the actual free carrier profile.
- The width of the spread is a few Debye length.
- Lower temperature can give better profile, but the trapping effect (or even donors) might become significant.

\[
L_D = \sqrt{\left(\varepsilon_r \varepsilon_0 k_B T / q^2 N_d \right)}
\]

\[
W = \sqrt{\frac{2\varepsilon_s}{q} \left( \frac{N_A + N_D}{N_A N_D} \right)} V_{bi}
\]

For one sided abrupt junction (p⁺n) : \( W \propto L_D \)
Donor and acceptor type traps

- If the traps cannot respond fast then the $N_D$ will be measured for donor type traps and $N_D - N_T$ for acceptor traps.
- If the traps can respond fast then the $N_D + N_T$ will be measured for donor type traps and $N_D$ for acceptor traps.

Space charge density under donor and acceptor traps
Deep Level Transient Spectroscopy

Illustrated for a p+n junction

- The sequence of applied biases
  - Initial reverse bias (steady state condition)
  - Forward bias filling pulse (fills up the traps)
  - Reverse bias emptying pulse (slowly empties the traps)
- Filling and emptying of the trap level can be done repetitively and hence the noise can be reduced by averaging
Rate window concept: effect of temperature

- The rate window technique gives the spectrum of the charges with trap depth energy proportional to the temperature and magnitude proportional to density

DLTS hole emission spectra for AlGaAs
Calculation of activation energy of traps

\[ \Delta C(t) = \Delta C(t = 0) \exp(-t / \tau_e) \]

\[ \tau_e = 1 / e_n \]

\[ e_n = \sigma_n v_{th} N_C \exp(-(E_C - E_{tr}) / k_B T) \]

\[ v_{th} \propto T^{1/2} \quad \text{and} \quad N_C \propto T^{3/2} \]

\[ \ln\left( \frac{e_n}{T^2} \right) \text{ vs. } 1000/T \text{ curve is a st. line} \]

For different trap levels, the temperature range to be chosen is very important (see Fig. 17 in handout)

The slope of the Arrhenius plot gives the trap energy. The intercept will give the capture cross section \( \sigma_n \)
Trap density from DLTS

\[ C \propto N_D^{0.5} \Rightarrow \frac{dC}{dN_D} \propto 0.5 N_D^{-0.5} \]

So,

\[ \frac{dC}{C} = 0.5 \frac{dN_D}{N_D} \]

Therefore approximately,

\[ \frac{\Delta C(t = 0)}{C_{dep, equil}} = 0.5 \frac{N_{trap}}{N_D} \]


Approximate because the difference in depletion depths \( x_{d2} - x_{d1} \) for two biases \( V_{a1} \) and \( V_{a2} \) are different from the trap filling depths \( x_{cr2} - x_{cr1} \), \( dN_D \) is not equal to \( N_{trap} \) over the entire region