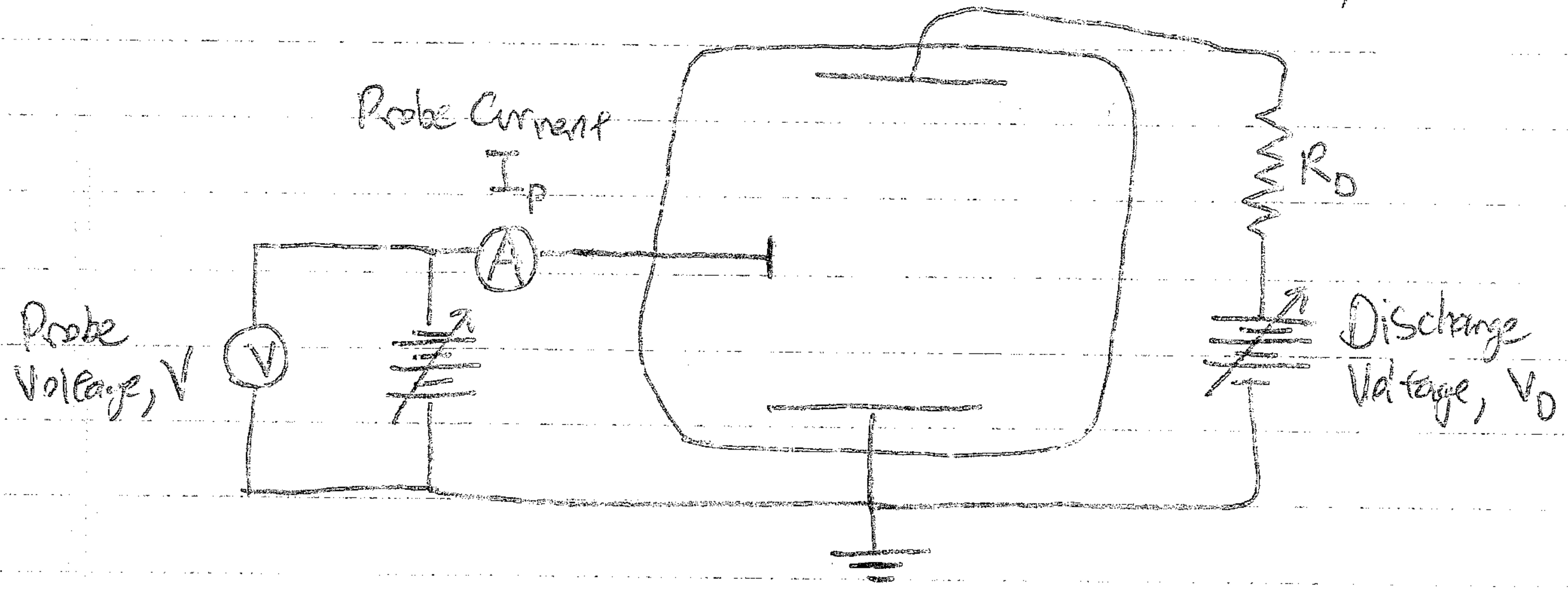
Lecture #20 Langmuir Probes, Atomic Processes, and Plasma Generation

Howes (1)

# I. Langmuir Probes

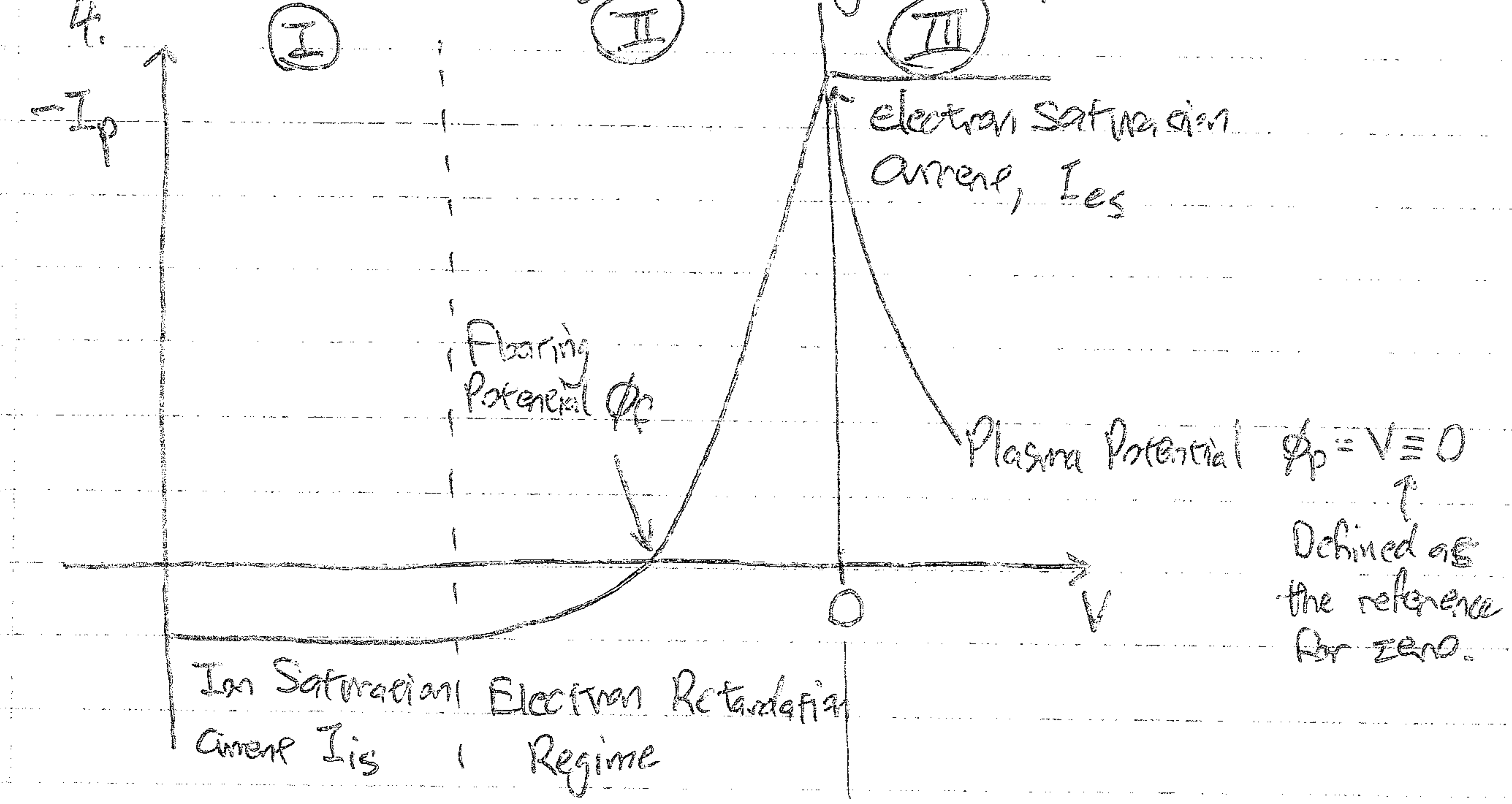
## A. Diagnostic of Electron Temperature $T_e$ and Density $n_e$

1. Langmuir probes are small metal electrodes inserted into a plasma
2. For a cool, low density plasma, it enables one to determine electron temperature $T_e$ and electron density $n_e$




3. Sweep probe voltage from negative to positive and measure current $I_p$

4\.



Lecture #20 (Continued) Hawes (3)

I. (Continued)

B. Ion Saturation Current

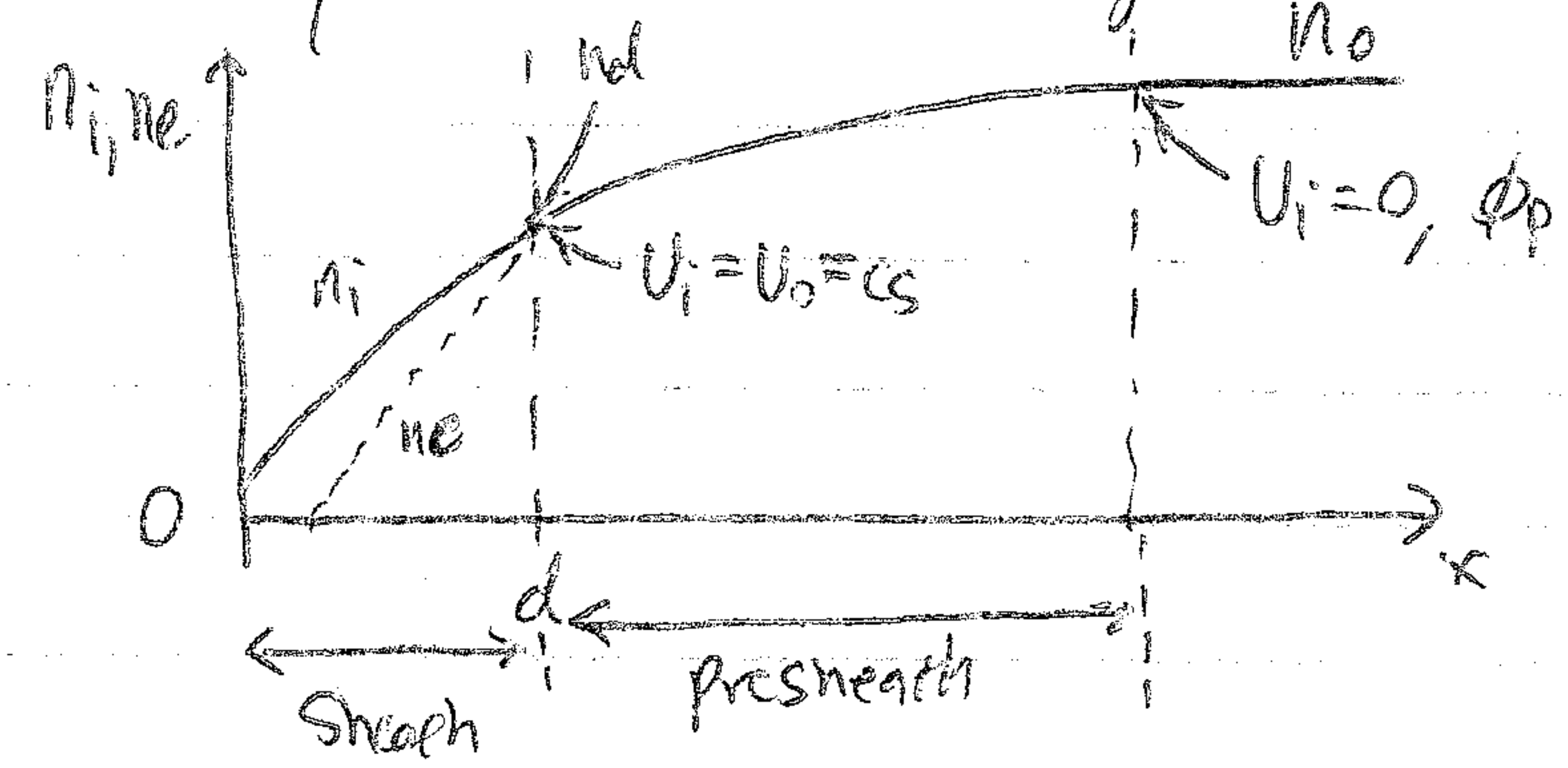
1. For a sufficiently negative probe potential, all electrons are prevented from reaching the probe, and you only get the ion current

2. From our study of the plasma sheath, we know the ion current is constant across the sheath (from the ion continuity equation). The ion current is therefore determine by the conditions at the sheath edge:

$$I_{is} = n_d e u_0 A, \text{ where the Bohm criterion specifies } u_0 = c_s = \sqrt{\frac{T_e}{m_i}}$$

($A$: Probe surface area)

3. But we want to know the density in the unperturbed plasma, not the density at the sheath edge:




a. The ion momentum equation gives a conservation of energy condition that we can use to find $n_d$ as a function of $n_0$.

$$\underbrace{\frac{1}{2} m_i u_0^2 + e\phi(d)}_{\text{Sheath edge}} = \underbrace{\frac{1}{2} m_i \cancel{u_i^2}^{\,0} + e\phi_p}_{\text{unperturbed plasma}}$$

b. Taking $\phi_p = 0$ as reference for potential [different from $\phi(a) = 0$ choice last lecture], we get

$$\phi(d) = -\frac{\frac{1}{2} m_i u_0^2}{e} = -\frac{1}{2}\frac{m_i}{e}\frac{T_e}{m_i} = -\frac{T_e}{2e}$$

I.B. (Continued)

3. (Continued) c. In presheath $n_i = n_e = n_0 e^{+\frac{e\phi}{T_e}}$, where the density $n_0$ is unperturbed plasma density at $\phi = \phi_p = 0$.

d. Substituting $\phi(d) = -\frac{T_e}{2e}$, we get $n_i(d) = n_0 e^{\frac{e\left(\frac{-T_e}{2e}\right)}{T_e}} = n_0 e^{-\frac{1}{2}} \simeq \underbrace{0.61 n_0}_{\text{Density at sheath edge.}}$

4. Therefore,

$$\boxed{I_{is} = 0.61 n_{i0}\, e \sqrt{\frac{T_e}{m_i}}\, A}$$

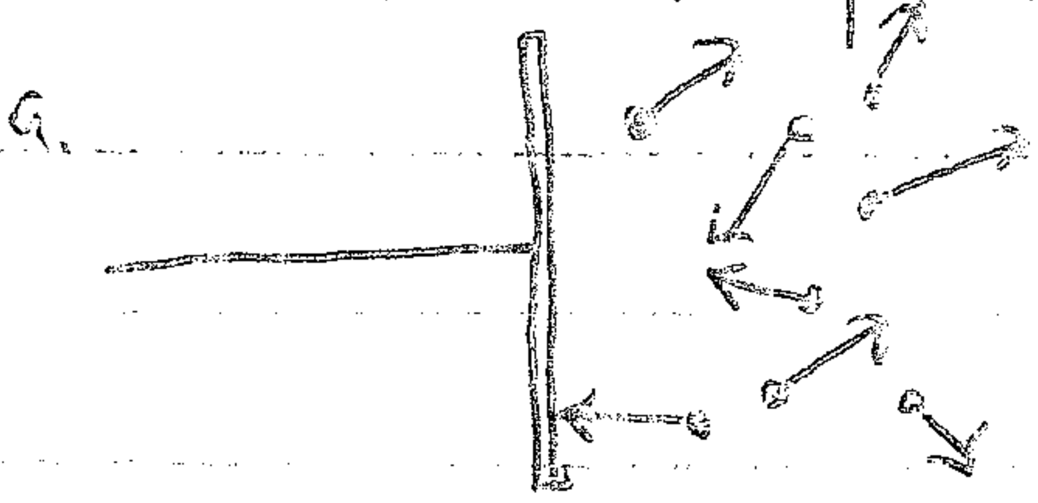
If we can find $T_e$, this gives $n_{i0}$!

C. Electron Saturation Current

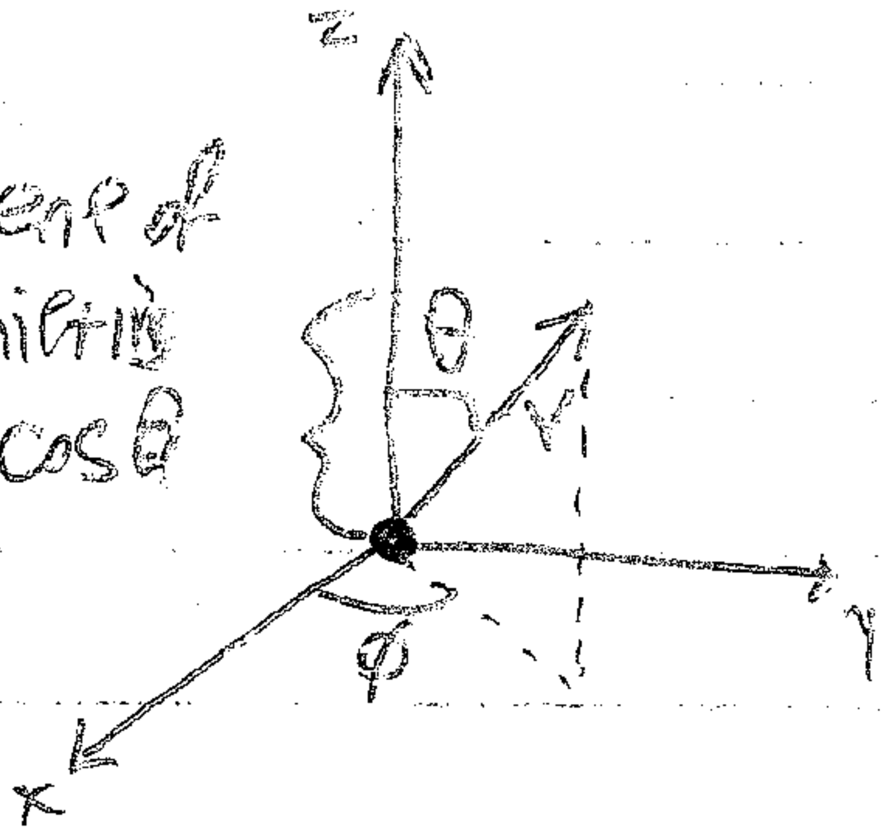
1. For a probe voltage that is positive w.r.t. plasma potential $\phi_p \equiv 0$, electrons are not hindered from reaching the probe.
   $\Rightarrow$ There is no sheath formation.

2. All electrons in positive half-plane of Maxwellian distribution will reach the probe:

a.



b. Component of velocity hitting probe, $v\cos\theta$




3. We must integrate over half plane of distribution $f_e(v) = \frac{n_{0e}}{\pi^{\frac{3}{2}} v_{Te}^3} e^{-\frac{v^2}{v_{Te}^2}}$,

a. $$I_{es} = -eA \int_{\text{half plane}} d^3\underset{\sim}{v}\, v\cos\theta\, f_e = -eA \underbrace{\int_0^{2\pi} d\phi}_{=2\pi} \underbrace{\int_0^{\pi/2} d\theta \sin\theta\cos\theta}_{=\frac{\sin^2\theta}{2}\Big|_0^{\pi/2} = \frac{1}{2}} \underbrace{\int_0^\infty dv\, \frac{v^3 e^{-\frac{v^2}{v_{Te}^2}}}{\pi^{\frac{3}{2}} v_{Te}^3} n_{0e}}_{\frac{v_{Te} n_{0e}}{\pi^{\frac{3}{2}}}\int_0^\infty dy\, y^3 e^{-y^2} = \frac{1}{2}\frac{v_{Te} n_{0e}}{\pi^{\frac{3}{2}}}}$$

$$= -eA(\cancel{2}\pi)\left(\frac{1}{\cancel{2}}\right) \frac{v_{Te} n_{0e}}{2\pi^{\frac{3}{2}}} = -\frac{eA n_{0e}}{2\pi^{\frac{1}{2}}}\sqrt{\frac{2T_e}{m_e}}$$

b. Thus $$\boxed{I_{es} = -\frac{1}{2} n_{0e}\, e \left(\frac{2T_e}{\pi m_e}\right)^{\frac{1}{2}} A}$$

I. C. (Continued)

4. NOTE: Ratio $\dfrac{|I_{es}|}{I_{is}} = \dfrac{+\frac{1}{2} n_{0e} e \left(\frac{2 T_e}{\pi m_e}\right)^{\frac{1}{2}} A}{0.61 n_{0i} e \left(\frac{T_e}{m_i}\right)^{\frac{1}{2}} A} = \dfrac{1}{0.61 (2\pi)^{\frac{1}{2}}} \sqrt{\dfrac{m_i}{m_e}}$

Quasineutrality $-n_{0e} e + n_{0i} e = 0$

So $\dfrac{|I_{es}|}{I_{is}} = 0.65 \left(\dfrac{m_i}{m_e}\right)^{\frac{1}{2}}$. Since $m_i \gg m_e$, $|I_{es}| \gg I_{is}$.

D. Electron Retardation Current

1. In this regime, it can be shown that:

a. $$I_e(V) = I_{es}\, e^{\frac{e(V-\phi_p)}{T_e}} = I_{es}\, e^{\frac{eV}{T_e}}$$

2. Taking the ln of this equation, we find:

$$\ln(|I_e|) = \ln(|I_{es}|) + \frac{e}{T_e} V$$

slope is inversely proportional to $T_e$.

3. To determine the electron temperature:

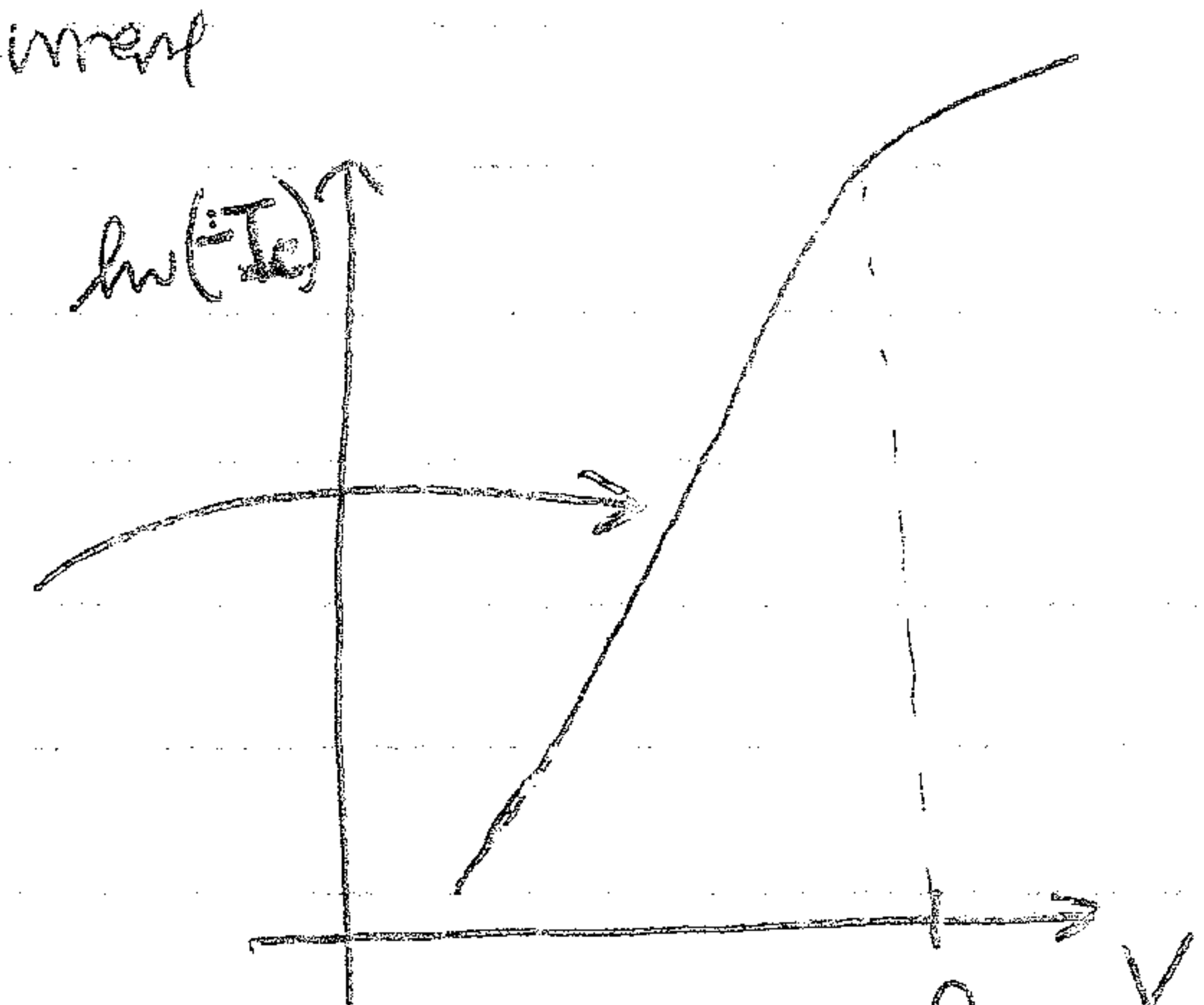
a. Determine ion saturation current $I_{is}$

b. $\underbrace{I_e(V)}_{\text{electron current}} = \underbrace{I_p(V)}_{\text{probe current}} - \underbrace{I_{is}}_{\text{ion current}}$

c. Plot a semi-log plot

Slope $= m = \dfrac{e}{T_e}$

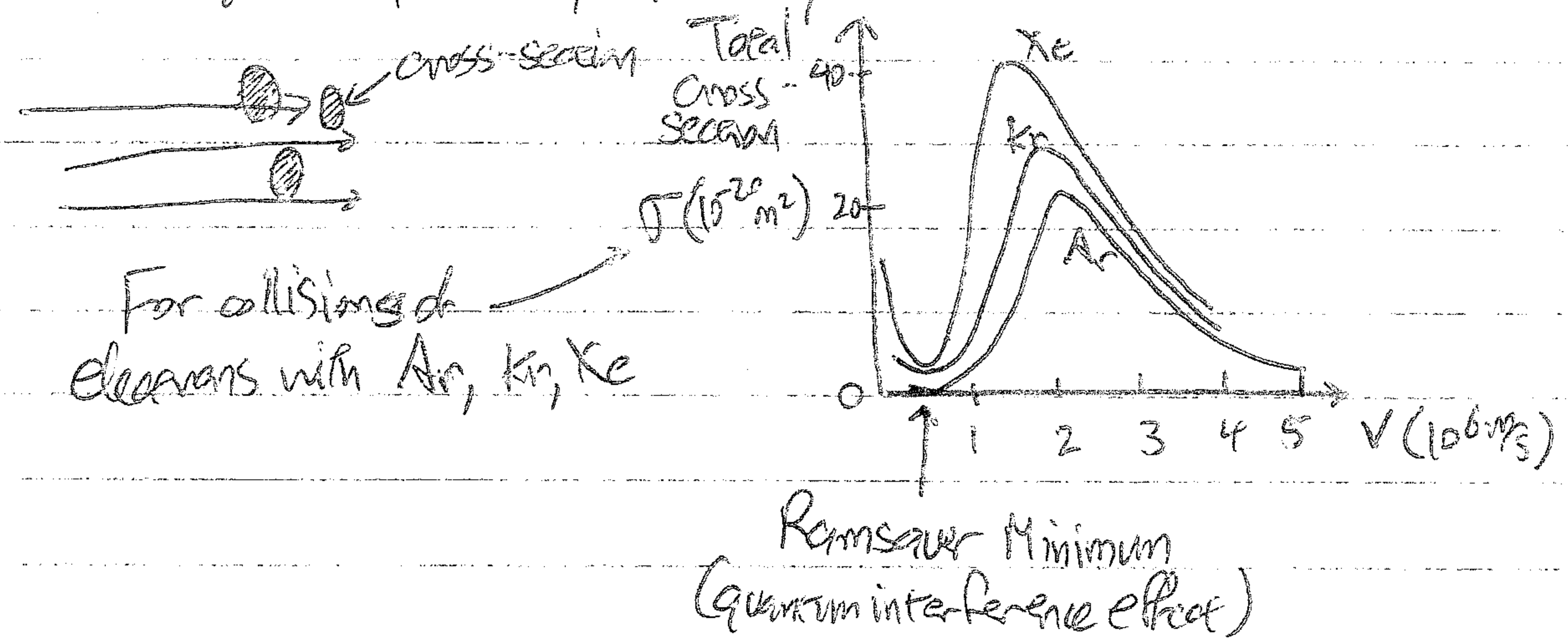
$\rightarrow \boxed{T_e = \dfrac{e}{m}}$ ← slope



# II. Atomic Collisional Processes

## A. Cross-Sections

1. Collisions between charged particles (usually electrons) and neutral atoms can lead to ionization of the atom
2. Such collisional ionization is an important way to generate plasmas.
3. We quantify the probability of collisions as a cross-section, $\sigma$




4. For a gas of atoms with density $n_a$,

   a. Mean free path $\lambda_{mfp} = \dfrac{1}{n_a \sigma}$

   b. Collision frequency $\nu_{coll} = \sigma v n_a$

   collision cross-section; velocity of charged particle

## B. Ionization Rate Coefficient

1. If we want to know the rate of ionization in a gas with electron temperature $T_e$, we must average over velocity distribution,

$$f_e(v) = \frac{n_e}{\pi^{3/2} v_{te}^3} e^{-\frac{mv^2}{2T_e}} \qquad v_{te}^2 = \frac{2T_e}{m_e}$$

2. Rate coefficient is defined as the average over distribution

$$\langle \sigma_{ion} v \rangle = \frac{1}{n_e} \int_0^\infty \sigma_{ion}(v)\, v f_e(v)\, dv$$

II. B. (Continued)

3. The <u>ionization frequency</u> is then $\nu_{ion} = n_a \langle \sigma_{ion} v \rangle$

4. Total Ionization rate (per volume per second)

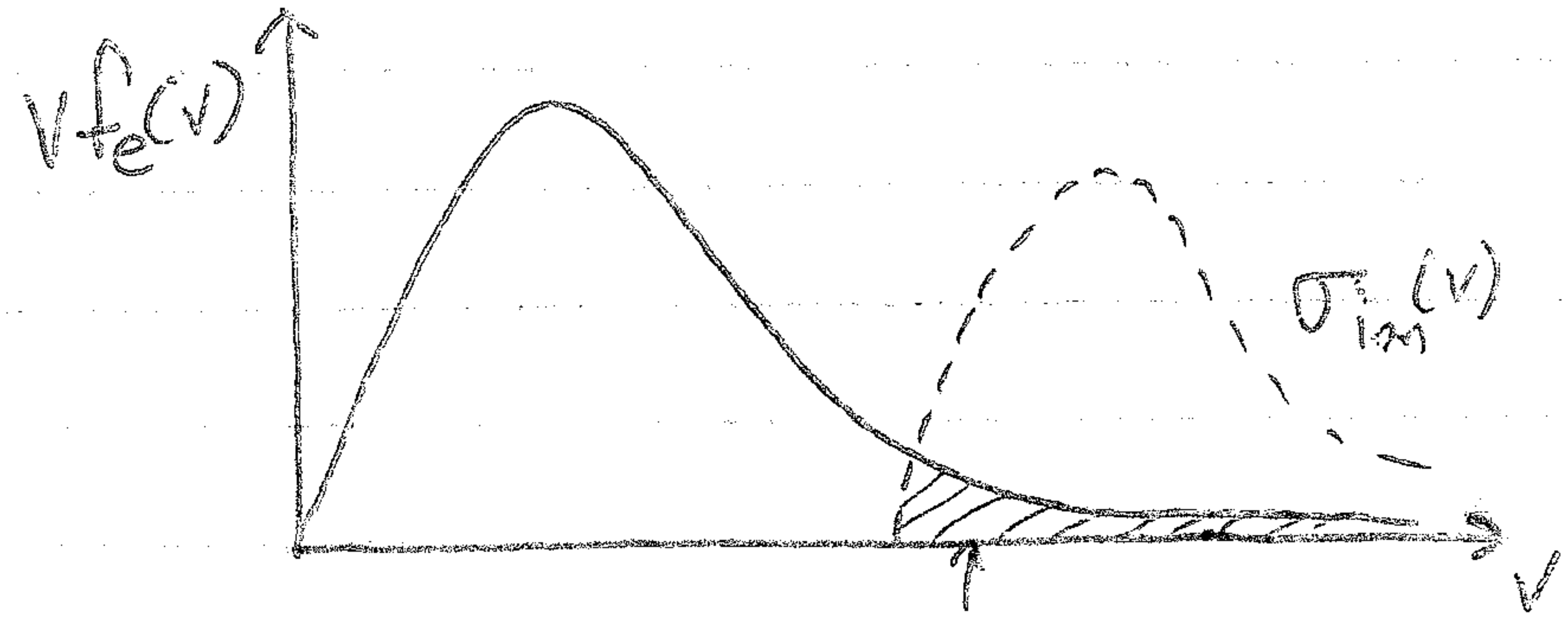
$$S_{ion} = n_e n_a \langle \sigma_{ion} v \rangle$$

C. <u>Electron Impact Ionization</u>

1. a. Typical low pressure gas discharges have $T_e \sim 3\,eV$

b. But ionization energy is much larger, e.g. for argon, 15.8 eV

2. Ionization rate is determined by tail of distribution



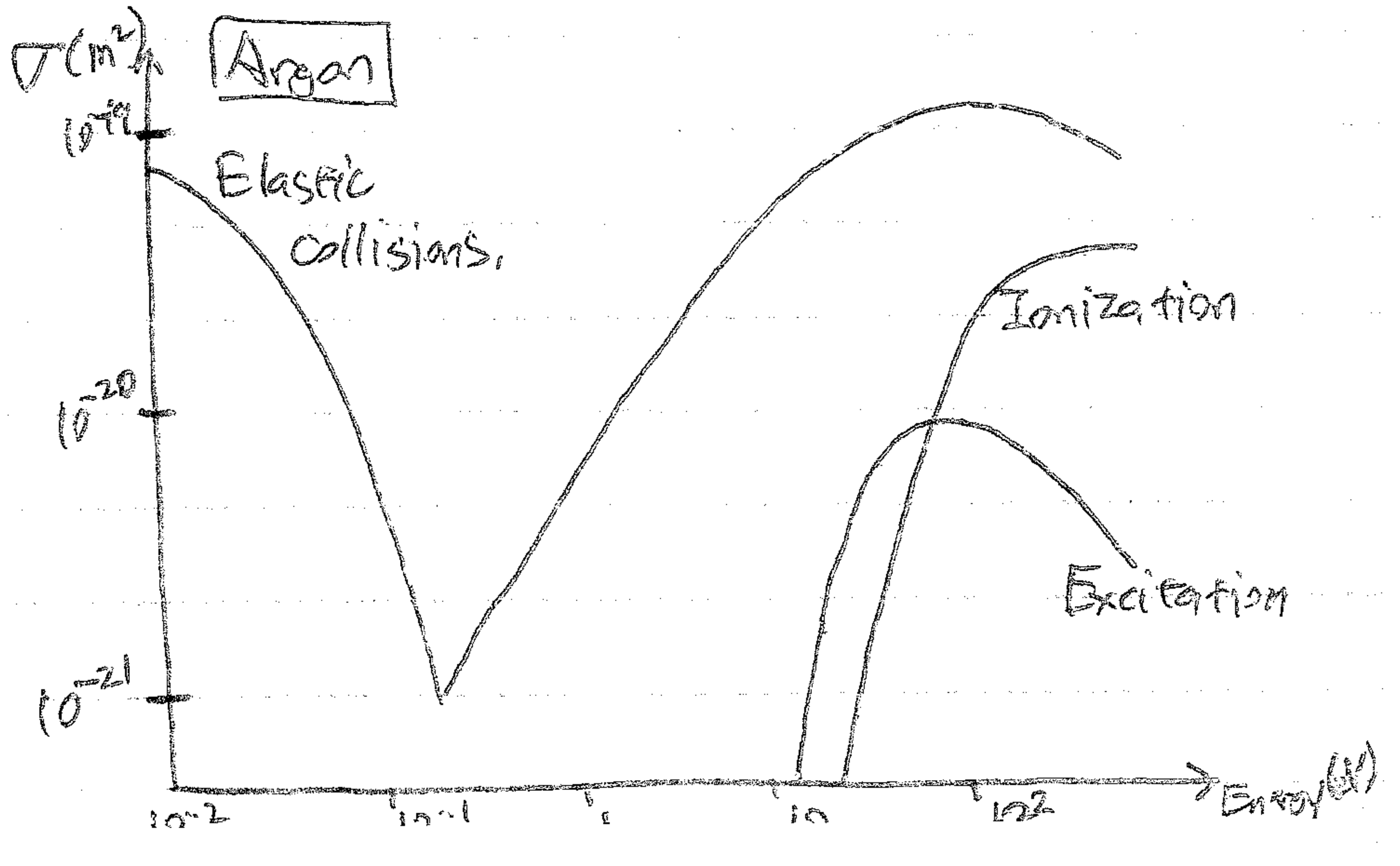

High energy electrons in tail are responsible for ionization.

3. For electron collisions with atoms, other processes can occur:

a) Elastic collisions

b) Ionization

c) Excitation



Lecture #20 (Continued)

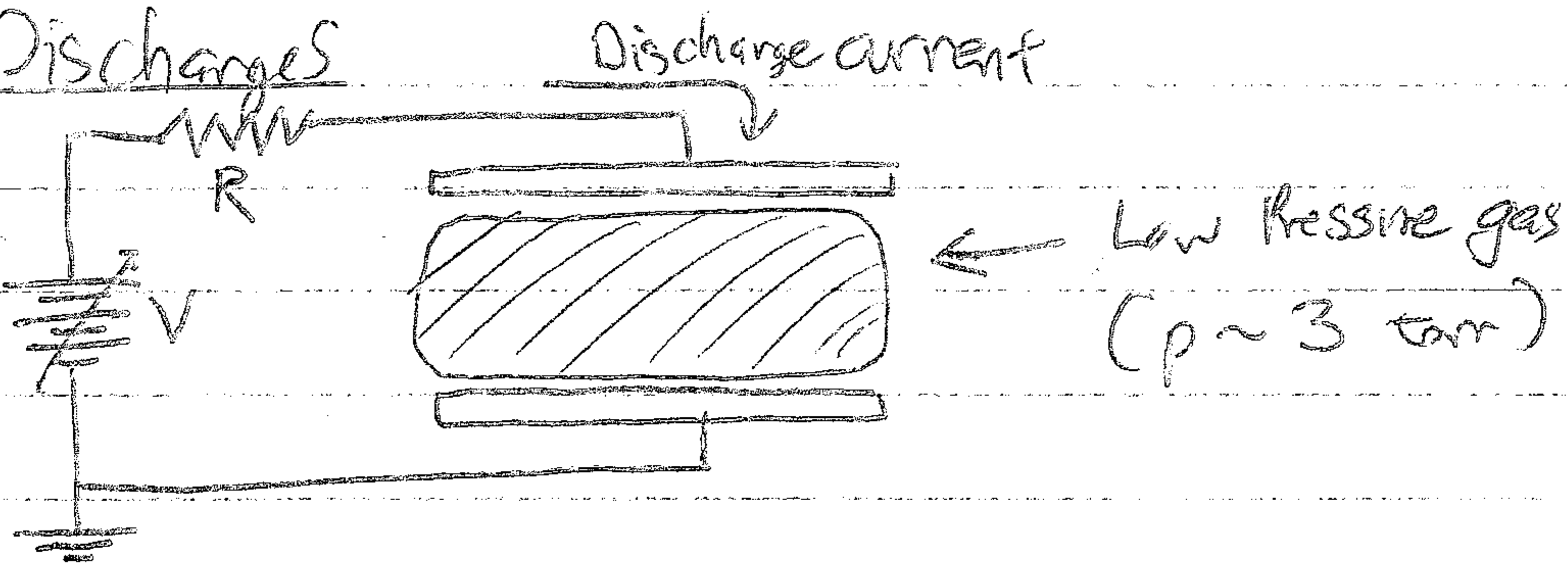
# III. Plasma Generation

## A. General Types of Discharges

1. DC Discharges
2. Capacitive RF Discharges
3. Inductively Coupled Discharges

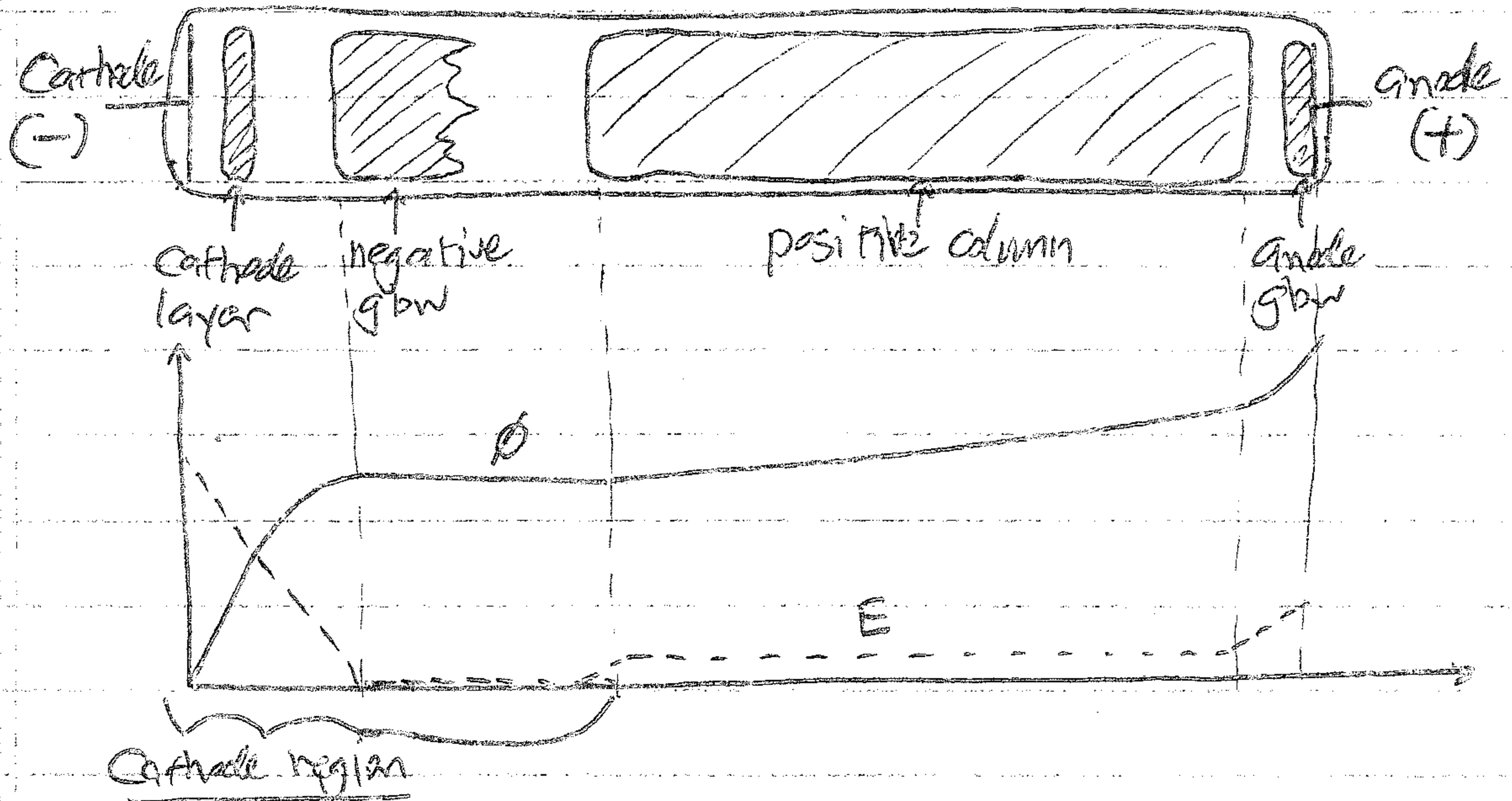
## B. DC Discharges

1.




a. Power supply chosen high enough so breakdown occurs, V ~ 600 V
b. Resistor in series to limit current after breakdown.

2. Glow discharge in long glass tube: (Fluorescent or neon lights)

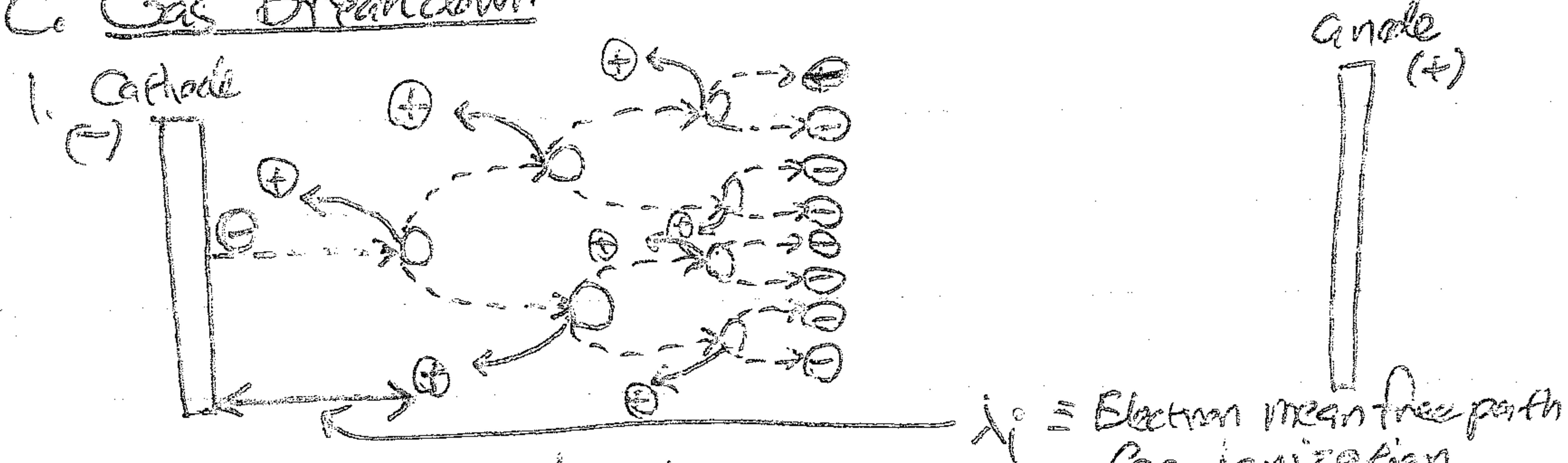



liberates electrons
from cathode to cause
electron impact ionization

Lecture #20 (Continued)

III. C. Gas Breakdown

1.



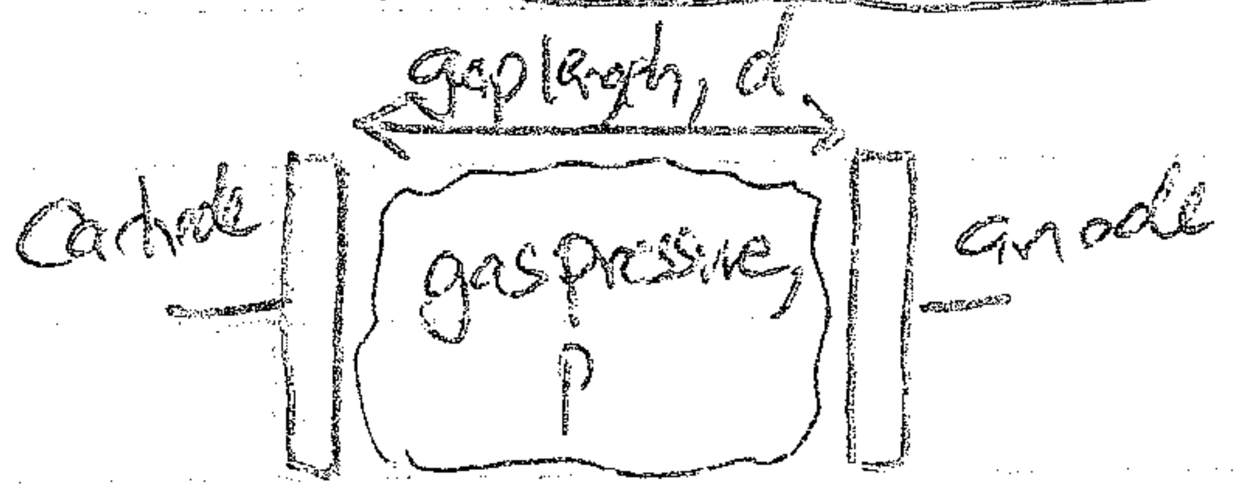

Electron avalanche

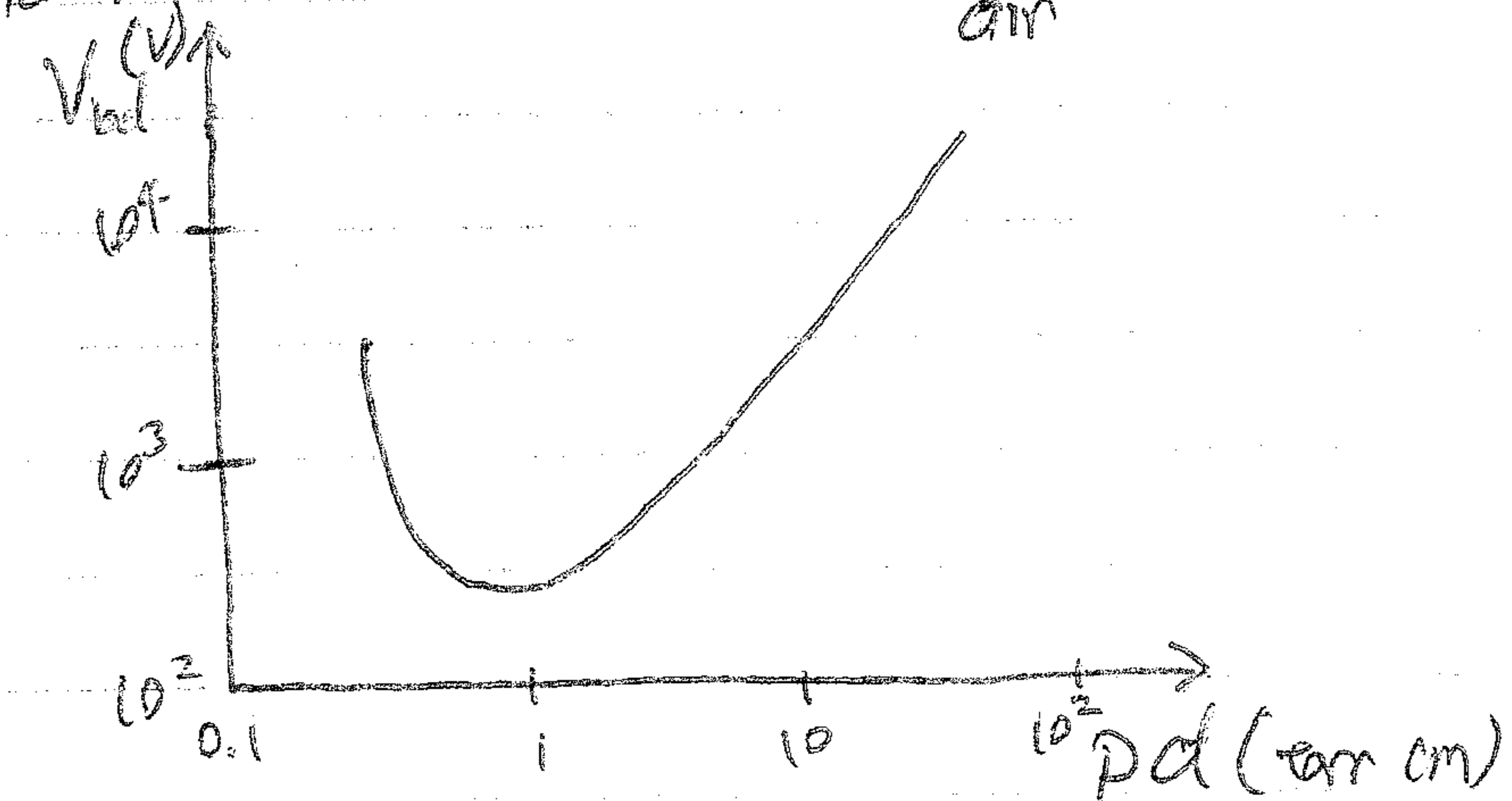
2\. a. Ions released from ionization collisions impact the cathode

b. These ion impacts can release more electrons to continue the process

c. Breakdown occurs when enough electrons are released to maintain the avalanche.

3\. Paschen Curve:




a. Minimum in breakdown voltage vs. (pressure)×(gap length)

b. Left of minimum, too few atoms for ionization

c. Right of minimum, energy gain per mean free path is too little energy for ionization

d. Hence, a higher electric field is required for breakdown.

4\.

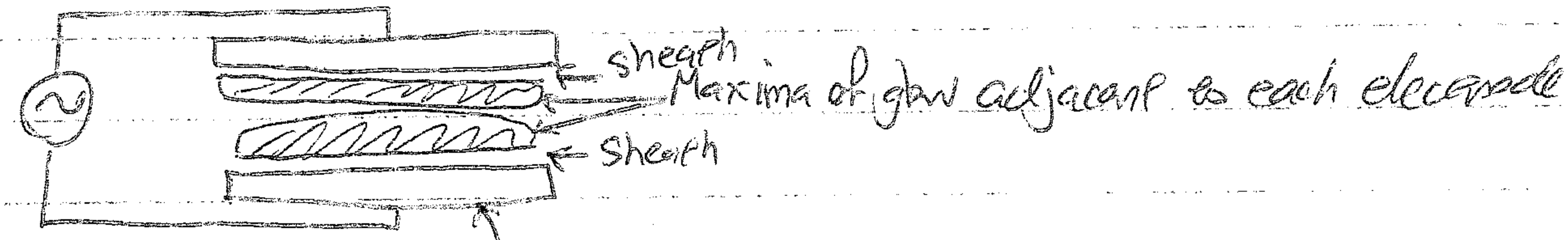
| Gas | Cathode | $V_{min}$ (V) | $(pd)_{min}$ (torr cm) |
|---|---|---|---|
| He | Fe | 150 | 2.5 |
| Ar | Fe | 265 | 1.5 |
| Air | Fe | 330 | 0.57 |
| Hg | W | 425 | 1.8 |

III. D. Thermionic Emitters

1. Cold cathodes require high voltages (300 - 3000 V) to achieve breakdown
2. Heated cathodes can release electrons more readily, requiring a smaller voltage drop.
3. Hot metal or oxide cathodes: W, $LaB_6$, BaSrO

E. Capacitive Radio-Frequency (RF) Discharges

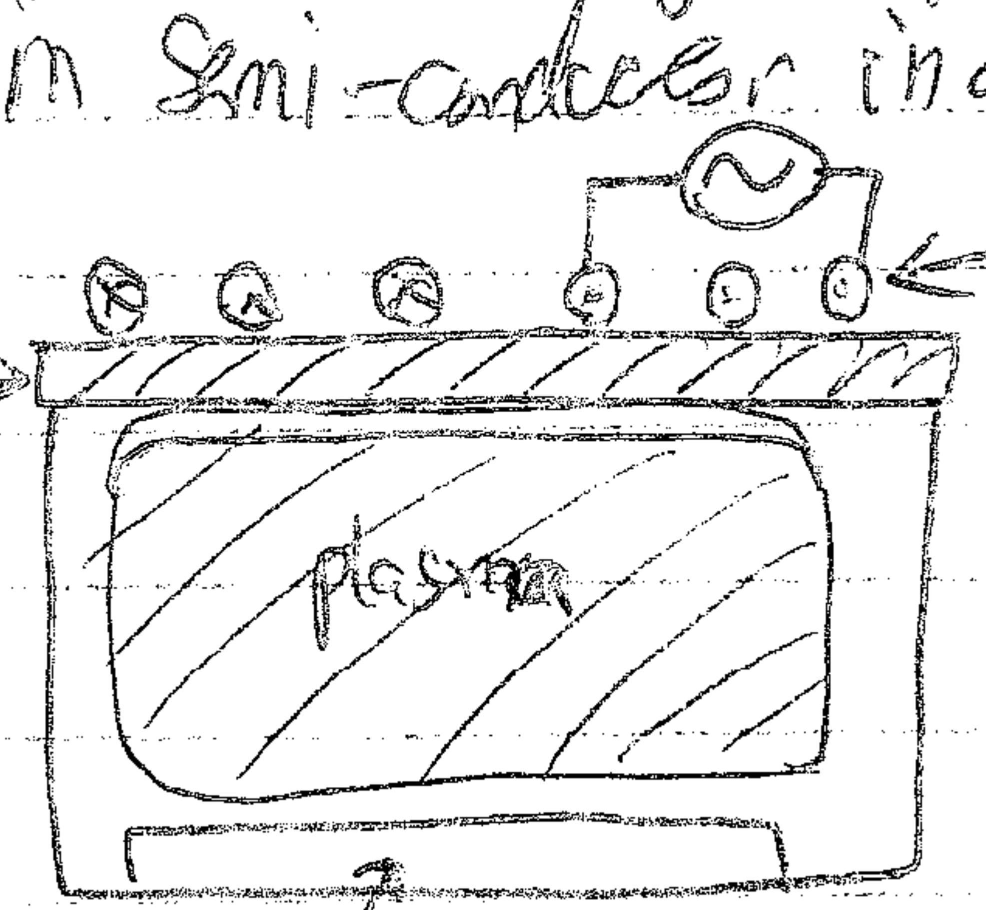
1. Parallel plate discharges f = 13.56 MHz
2. Electrons gain a thermal energy of a few eV, enough to lead to ionization
3. Frequently used for plasma processing: a) plasma etching
   b) Plasma-enhanced chemical vapor deposition (PECVD)
4.




RF electric fields result from surface charges on electrodes.

F. Inductively Coupled Plasmas

1. Can achieve higher plasma densities for plasma processing in semi-conductor industry
2.




a. Electric field in plasma is generated by a time-varying magnetic field