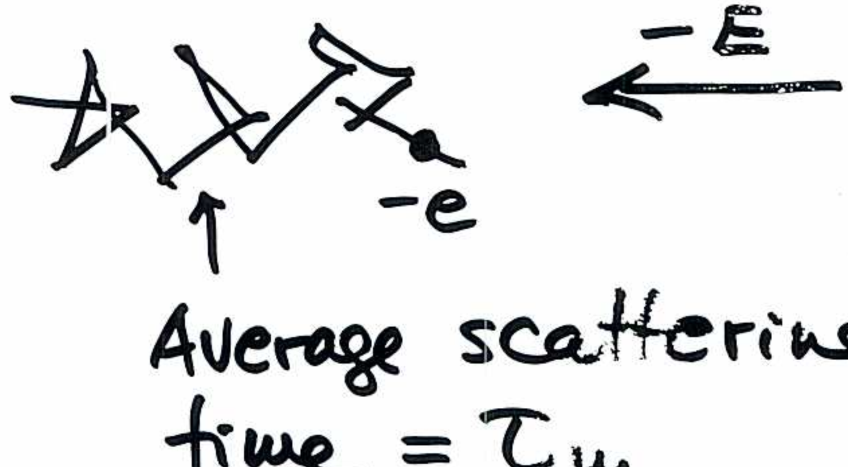
CHARGE-CARRIER "INERTIA" IN SEMICONDUCTORS

?

or

IS σ A FUNCTION OF FREQUENCY?

BASIC PICTURE OF HOW σ ARISES



Momentum-conservation $\Rightarrow$

$$\frac{dp}{dt} = eE - \frac{p}{\tau_m} \qquad (p = \langle p \rangle)$$

Steady state: $\frac{dp}{dt} = 0$

$$p = \underline{eE\,\tau_m}$$

$p = \hbar k$; gr. vel. $v = \frac{\hbar k}{m^*}$

$$v = \frac{eE\tau_m}{m^*}$$

$$\boxed{\mu \equiv \frac{v}{E} = \frac{e\tau_m}{m^*}}$$ DC CASE

$$\left(\sigma = ne\mu = \frac{ne^2\tau_m}{m^*}\right)$$

NEXT: $E = E_0 \cdot e^{j\omega t}$

How fast do electrons respond?

Phase factor?

Assume that $v = v_0 \cdot e^{j\omega t}$

$$\frac{d}{dt}\left(m^* v_0 e^{j\omega t}\right) = eE_0 \cdot \cancel{e^{j\omega t}} - \frac{m^* v_0 \cdot \cancel{e^{j\omega t}}}{\tau_m}$$

$$j\omega m^* v_0 = eE_0 - \frac{m^* v_0}{\tau_m}$$

$$v_0(1+j\omega\tau_m) = \frac{e\tau_m}{m^*}E_0$$

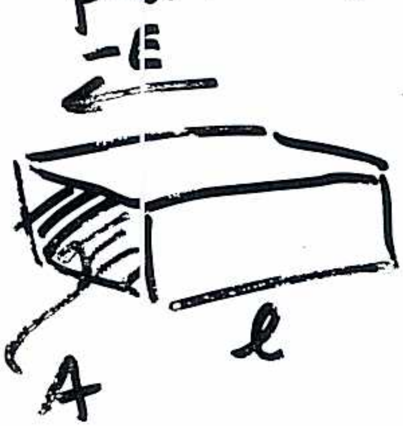
$$\boxed{\mu = \frac{v_0}{E_0} = \frac{\mu_0}{1+j\omega\tau_m}}$$

DC VALUE

$\Rightarrow$ μ COMPLEX!

$$\mu = \frac{\overbrace{\mu_0}^{\text{Real}}}{1+(\omega\tau_m)^2} - \frac{\overbrace{j\mu_0\omega\tau_m}^{\text{Imag.}}}{1+(\omega\tau_m)^2}$$

Real part $\Rightarrow$ CONDUCTANCE :



$$G = \frac{A\cdot\sigma}{l} =$$

$$= A\cdot\frac{ne\mu_r}{l}$$

Imag. part: $jB = \dfrac{A \cdot n e j \mu_i}{\ell} =$

$$= \frac{-jA n e \mu_o \omega \tau_m}{\ell\left(1 + (\omega\tau_m)^2\right)} \Rightarrow j\omega(-C)$$

where

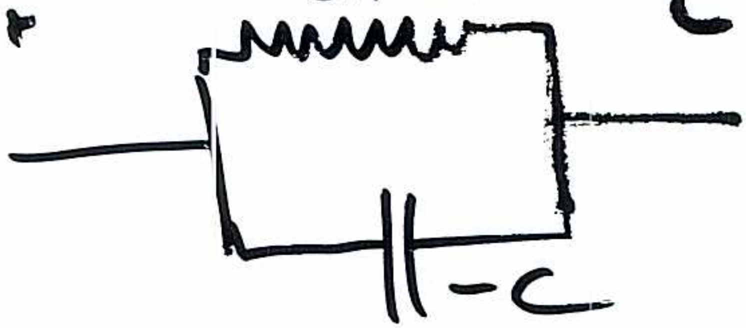
$C = C(\omega)$

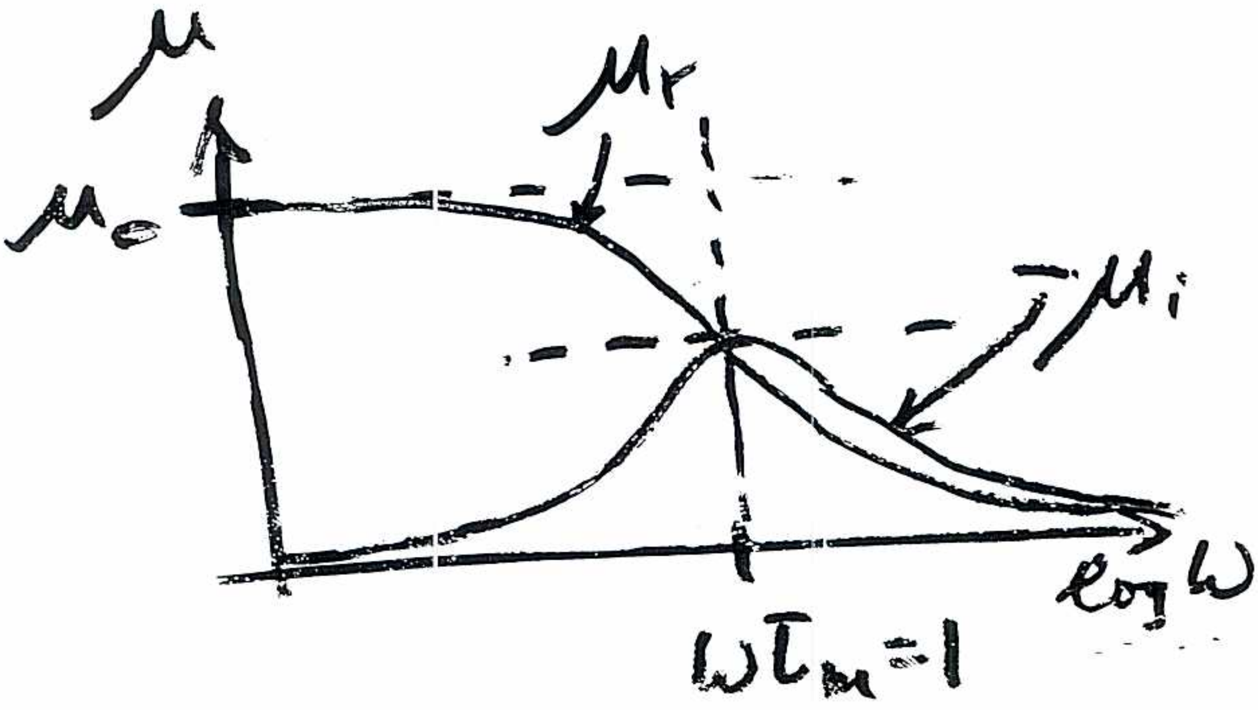
Total $\underline{Y = G + jB}$

$G(\omega)$

$G \propto \mu_r$

$$C = \frac{A n e \mu_o \tau_m}{\ell\left(1 + (\omega\tau_m)^2\right)}$$





rift region can enhance performance.

NT EFFECTS IN UNDEPLETED TAXIAL MATERIAL

diodes contain a region of undepleted is may be an inherent design feature, as nixer and transit-time devices, or it may e" region from the influence of contacts, mited control of fabrication tolerances. n and total length of this undepleted vary in a way determined by the total device. It is important to characterize of this material because its effect on operties can be significant, especially at vave) frequencies. In this section some his problem are briefly reviewed. Monte en used to characterize uniform, undematerial as a function of frequency and

of Undepleted Epitaxial Material

sis assumes no transient effects and a ity. The resulting equivalent circuit of naterial of length w, cross-sectional area tant ϵ is shown in Fig. 12(a). This is conductance in parallel with the cold nce. An extension of this analysis uses field characteristic [19], in which case mes signal-level dependent as shown in

approach to calculating transient transume a constant momentum relaxation um balance equation. This leads directly cy-dependent mobility [22]

$$(\omega) = \frac{\mu_0}{1 + (\omega\tau_m)^2} - \frac{i\mu_0 \omega\tau_m}{1 + (\omega\tau_m)^2} \quad (1)$$

frequency, low-field mobility and ω is y. The equivalent circuit implied by this

T performance of this signal-level dependent ous loss" have been analyzed by Blakey et al.

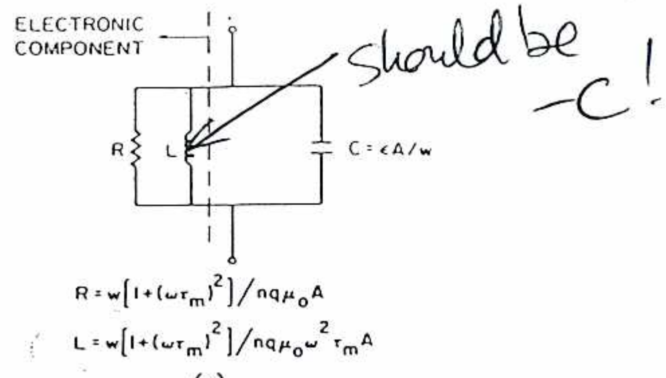


Fig. 12. Equivalent circuit representations of undepleted epitaxial material. (a) Low field, low frequency, (b) arbitrary field, low frequency, and (c) constant momentum relaxation time approximation.

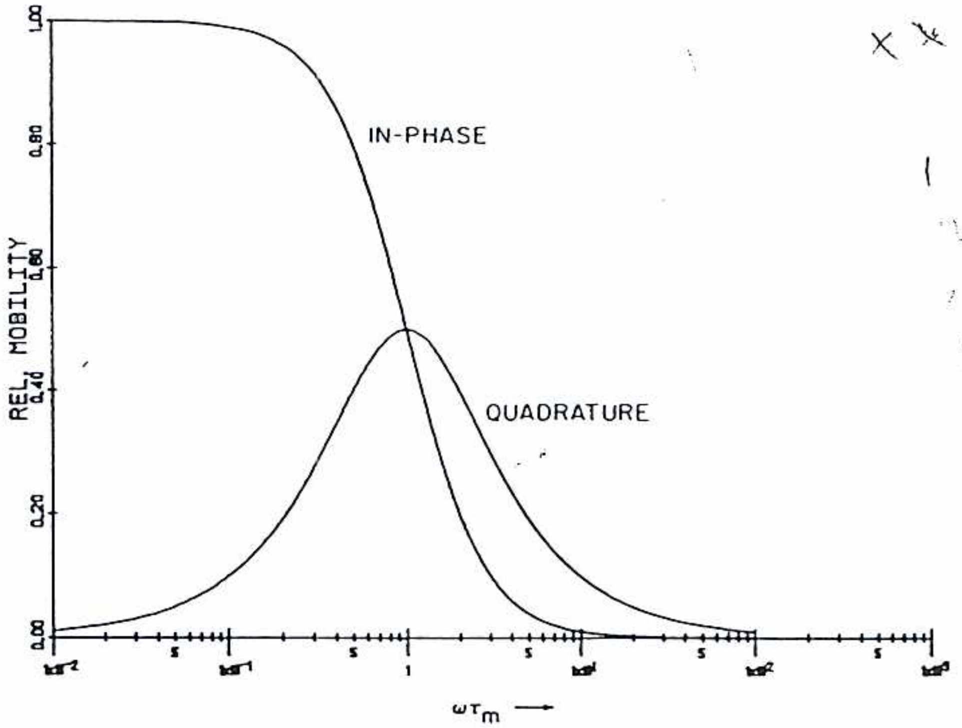
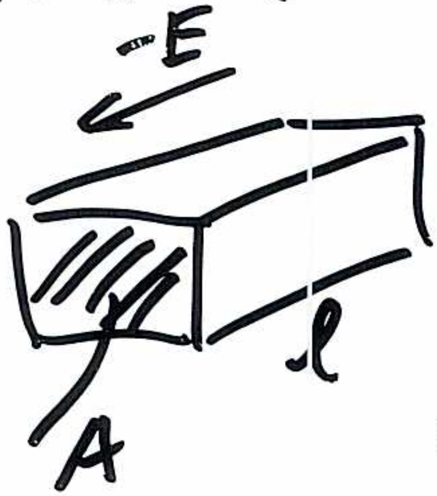


Fig. 13. Frequency dependence of in-phase and quadrature mobilities calculated in the constant momentum relaxation time approximation.

expression is shown in Fig. 12(c). Note that there is now an electronic susceptance which is predicted to be inductive. The frequency dependence of the real (in-phase) and imaginary (quadrature) mobilities is shown in Fig. 13. The in-phase mobility deteriorates monotonically as a function of frequency while the quadrature mobility peaks at $\omega\tau_m = 1$.

These analyses lead to the expectations that the conductance of undepleted epitaxial material decreases as frequency and signal level increase and that there is a significant inductive

It is easier to work with a series circuit:



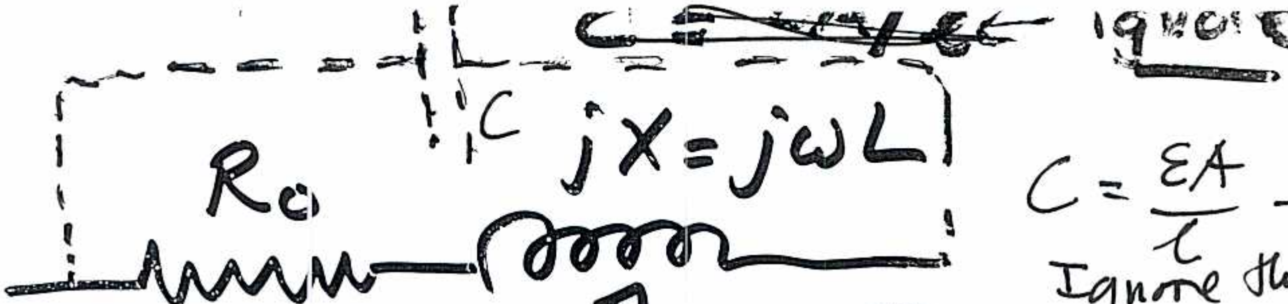
$$R = \frac{l}{A \cdot \sigma} = \frac{l}{A \cdot ne} \cdot \mathrm{Re}\left\{\frac{1}{\mu}\right\}$$

$$\frac{1}{\mu} = \frac{1 + j\omega\tau_m}{\mu_0}$$

$$R = \frac{l}{A n e \mu_0} = \overbrace{R_{DC}}^{R_0}\,!$$ (R not a function of ω!)

$$jX = \frac{l}{A n e \mu_0} \cdot j\omega\tau_m$$

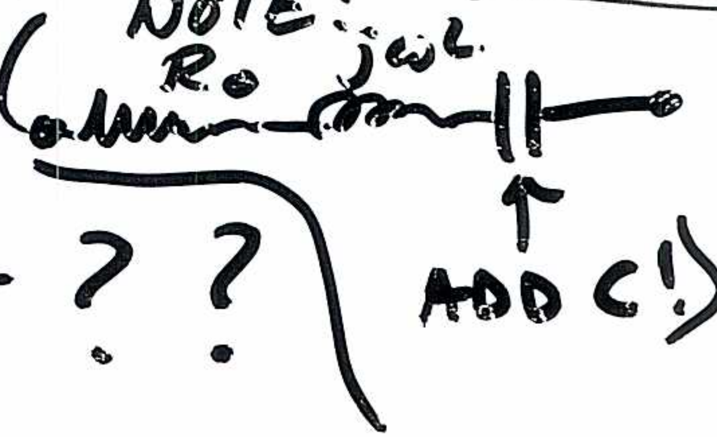
$$\boxed{Z = R + jX = R_0(1 + j\omega\tau_m)}$$



$C = \frac{\varepsilon A}{l} \rightarrow$ Ignore this!

$L = R_0 \cdot \tau_m$

NOTE:



SO WHAT??

ONLY IMPORTANT IF $\omega \tau_m \simeq 1$

FIND τ_m from μ_0

$$\mu_0 = \frac{e\tau_m}{m^*}$$

Ex.: GaAs, 300K, $m^* \simeq 0.067\, m_0$

$\mu_0 \simeq 6{,}000\ \mathrm{cm^2/Vsec}$

$\underline{\tau_m = 2.29 \times 10^{-13}\ \mathrm{sec}}$

$l = 0.5\mu$

$\omega \tau_m = 1$ for $f = 696$ GHz!

OR <u>0.696 THz</u>

MOST PEOPLE DON'T DO MICROWAVE-TYPE MEASUREMENTS AT 696 GHz!

($\lambda \cong 0.43$ mm)

BUT: COOL THE SAMPLE $\rightarrow$ HIGHER μ_0 $\rightarrow$ LONGER τ_m.

ASSUME "PURE" GaAs

AT 77K.

MONTE CARLO BY

JACK EAST AGAIN ⇒

$\mu_0 \simeq 30{,}000\ cm^2/Vs$.

$E_0 = 1kV/cm$ ($\simeq$ smallest possible for his program)

We predict

$\omega\tau_m = 1$ for

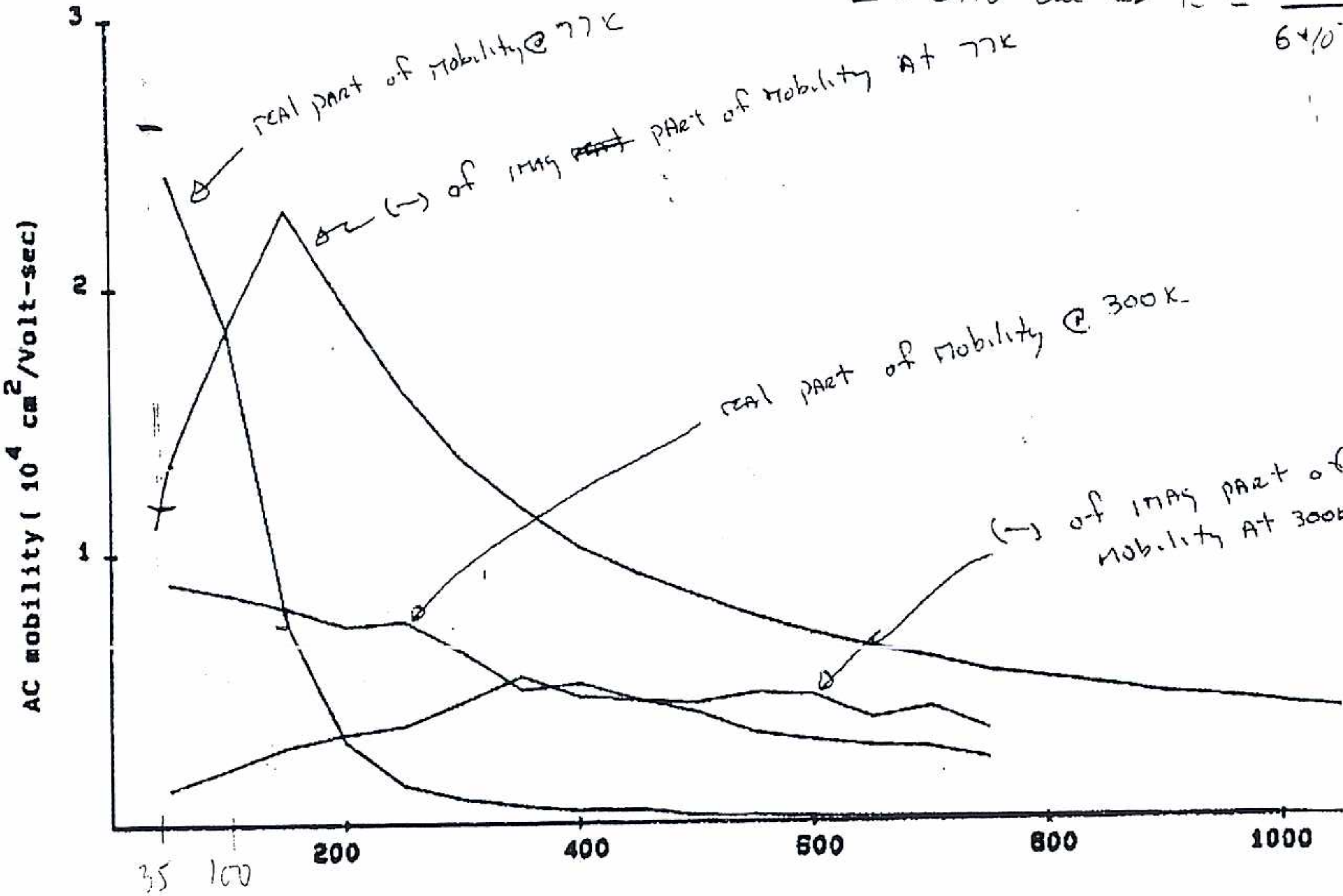
$$f = 696 \times \frac{6{,}000}{30{,}000}$$

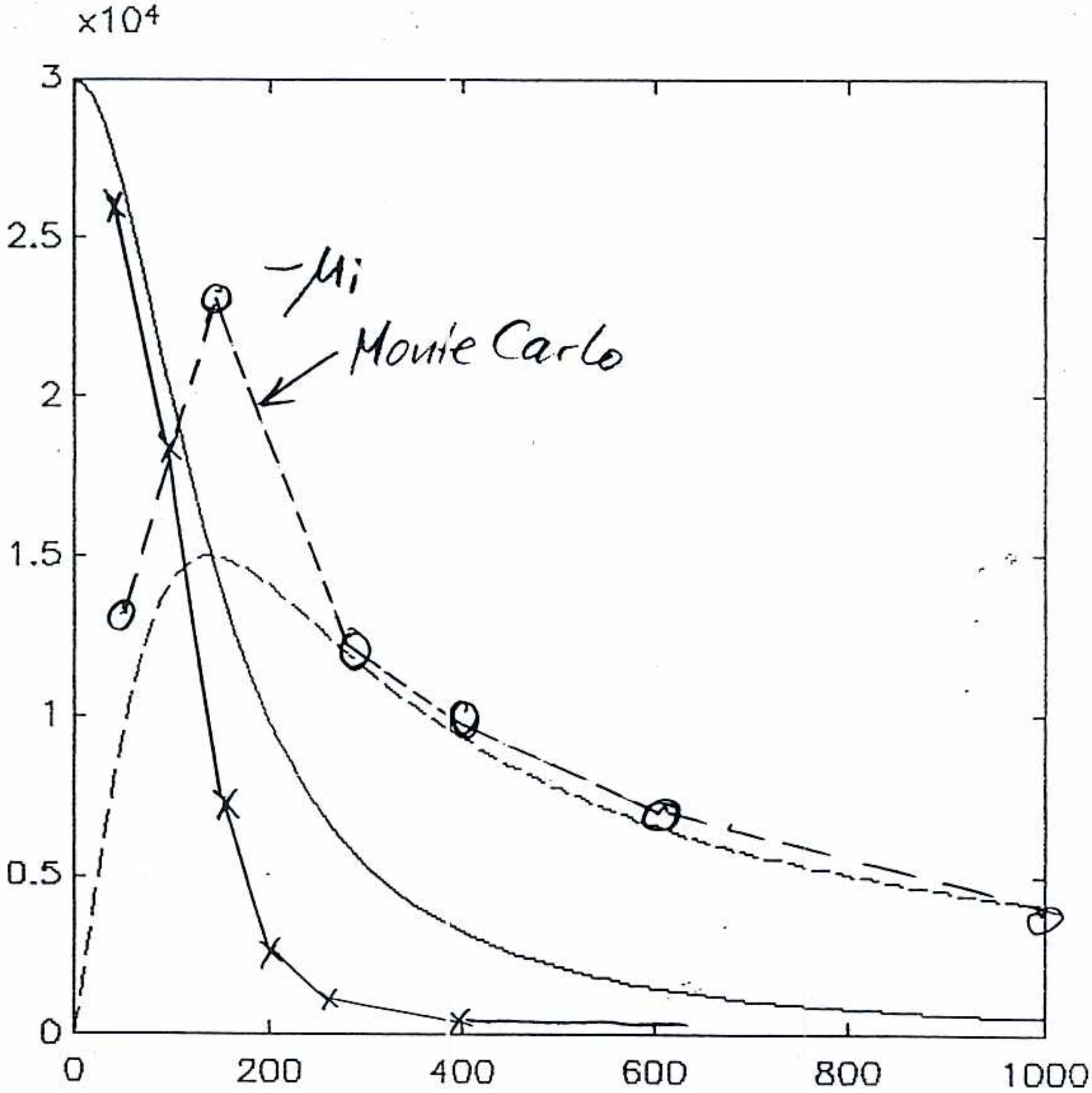
$= 139\ GHz$ ⇒ SEE PLOT!

— peak amplitude of field

$E = 1 kV/cm$; For wafer $V \approx 0.5V$

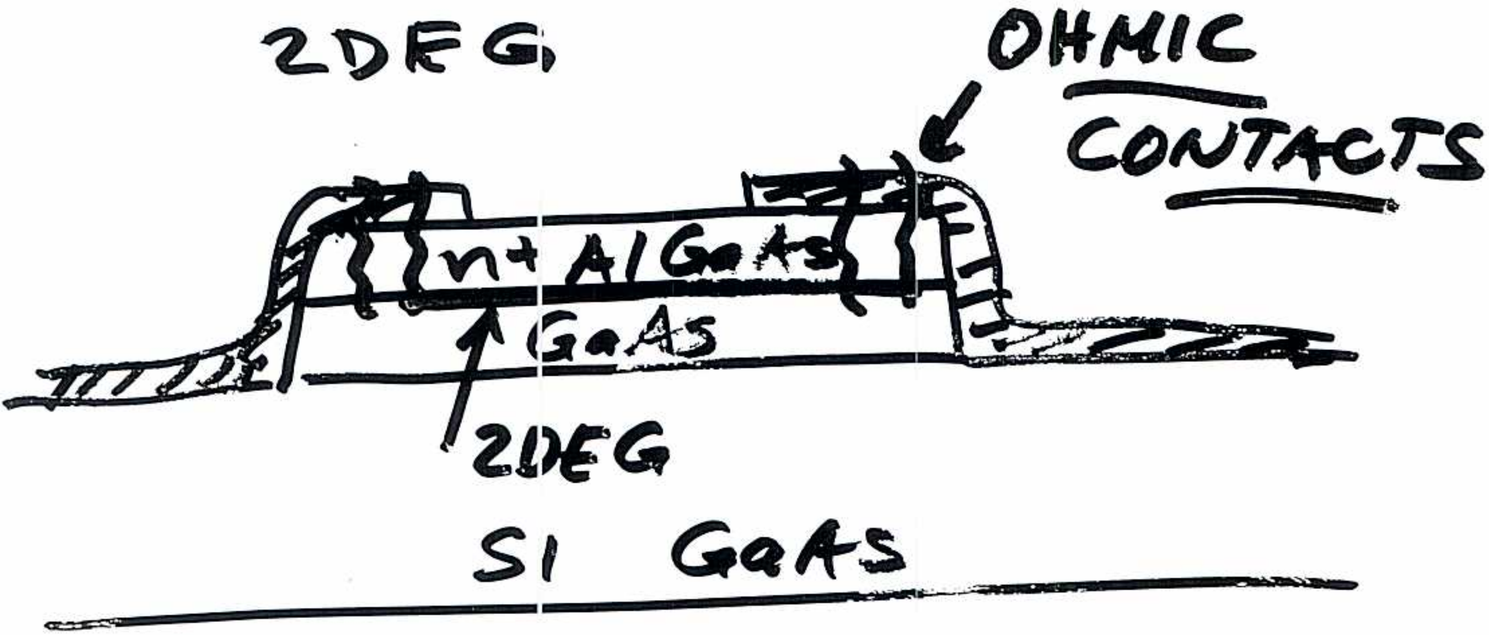
$L \approx 6 \times 10^{-4} cm \Rightarrow E = \frac{5 \times 10^{-1}}{6 \times 10^{-4}} \approx 1kV$





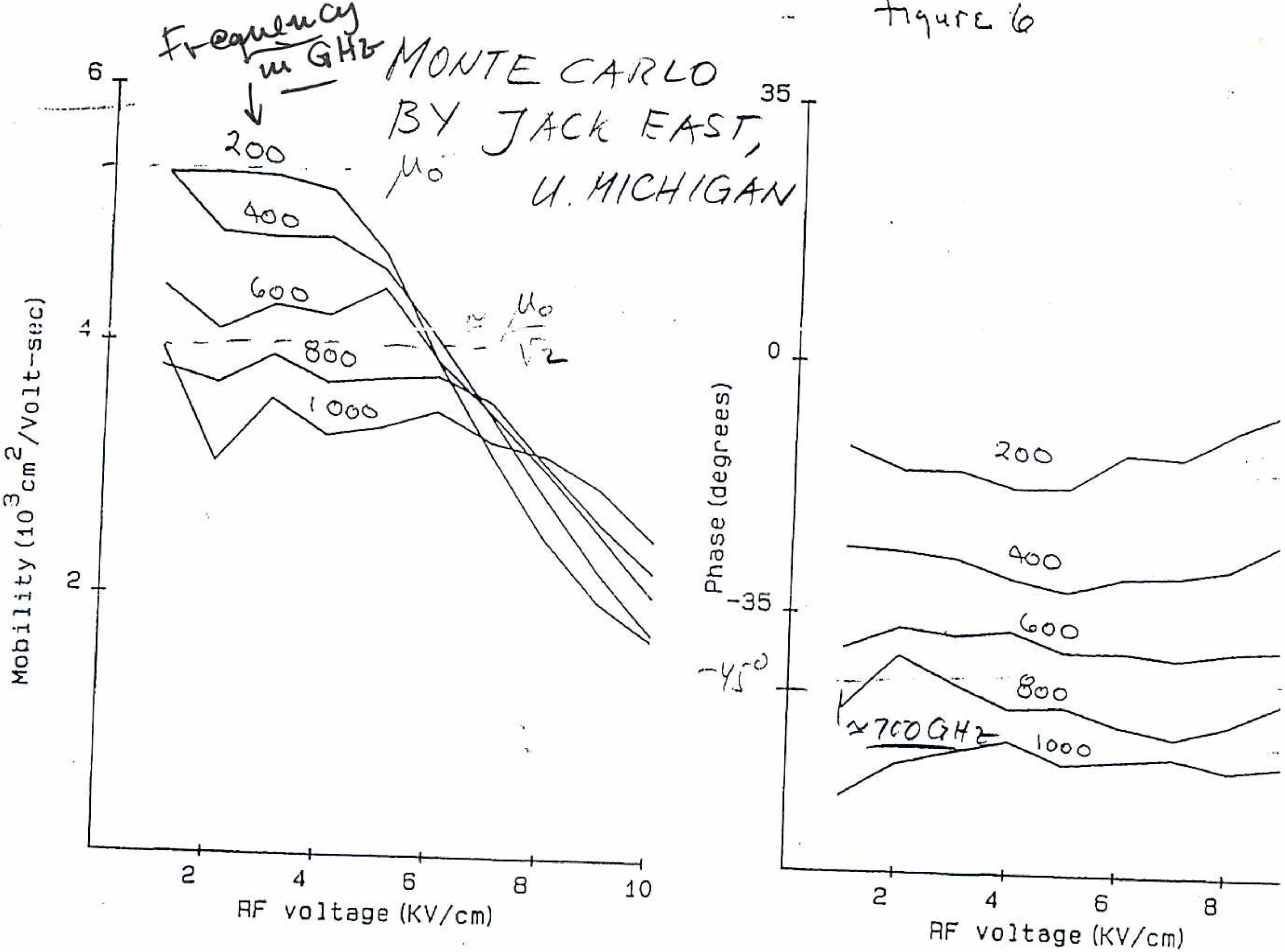
x10^4
3
2.5
2
1.5
1
0.5
0
0
200
400
600
800
1000
-Mi
Monte Carlo

EVEN BETTER:



T	μ	f_m, GHz
77K	~100,000	42
4.2K	~250,000	16.7

INDUCTANCE CAN BE MEASURED WITH CASCADE PROBE ....?! (AT 77K, figure 6


Frequency in GHz
MONTE CARLO
BY JACK EAST,
U. MICHIGAN
μ_0
$\approx \frac{\mu_0}{\sqrt{2}}$
200
400
600
800
1000
Mobility ($10^3 cm^2$/Volt-sec)
6
4
2
RF voltage (KV/cm)
2
4
6
8
10
Phase (degrees)
35
0
-35
-45^0
≈ 700 GHz
200
400
600
800
1000
RF voltage (KV/cm)
2
4
6
8