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ADVANCED TECHNIQUES FOR THE MEASUREMENT OF MULTIPLE RECOMBINATION PARAMETERS IN SOLAR CELLS

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Model Equations

$$n(x,t) = \sum_m A_m \phi_m(x) e^{-\lambda_m t} \qquad n(x,\omega) = \int \sum \frac{\phi_m(x)\phi^*_m(x)}{i\omega + \lambda_m} h(x)\,dx$$

$$A_m = \int_0^d n(x,o)\phi_m(x)\,dx \qquad h(x) \equiv \text{steady state excitation}$$

$$\sqrt{\frac{\beta_m}{D}}\, d \tan \sqrt{\frac{\beta_m}{D}}\, d = \frac{sd}{D} \qquad d \equiv \text{device length}$$

$$\lambda_m = 1/\tau + \beta_m$$

s AND μ DEPENDENCE IN BOTH EIGENVALUE AND EIGENMODE

τ DEPENDENCE ONLY IN EIGENVALUE

Model

EIGENVECTORS ϕ_M

DETERMINED BY μ AND BOUNDARY CONDITIONS

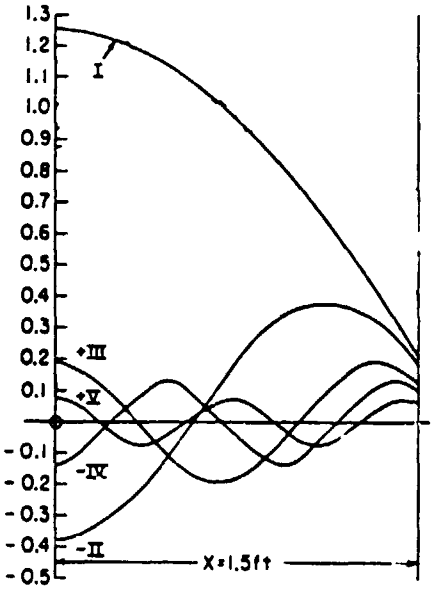


Fig. 3.1. Representation of the initial temperature distribution for $\theta = 1$ F by means of a Fourier series.

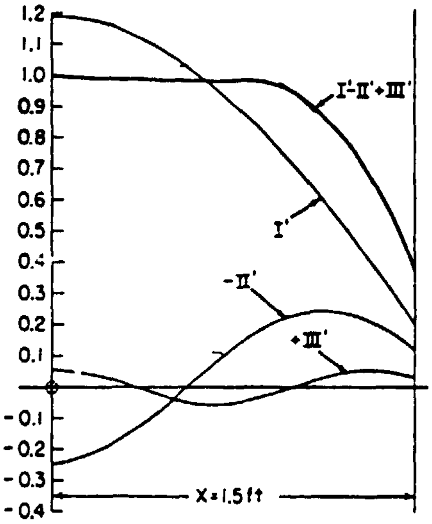
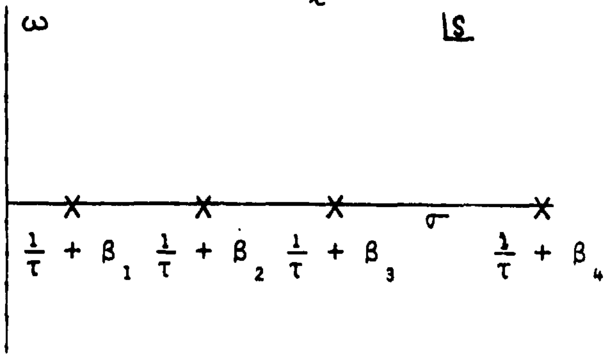


Fig. 3.2. Representation of the temperature distribution after 5 hr by means of a Fourier series.

EIGENVALUES (POLES) $\lambda_M = \beta_M + 1/\tau$

OVERALL DISPLACEMENT DETERMINED BY $1/\tau$

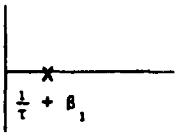
RELATIVE POSITION β_i DETERMINED BY μ BOUNDARY CONDTTIONS



Assumptions and Approximations

1. POLE POSITION
    - A. DOMINANT POLE

$e^{-t(\frac{1}{\tau} + \beta_1)}$



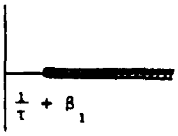
        1. BEST IN THIN DEVICES WHERE POLES ARE WELL SEPARATED
        2. LARGE TIME (DECAY) OR LOW FREQUENCY (MODULATIONS METHODS) FIRST POLE DOMINATES
        3. UNIFORM EXCITATION PREFERENTIALLY EXCITES FIRST MODE

    - B. FIRST POLE AT $1/\tau$
        1. ONLY TRUE FOR $\upsilon = 0$ AT BOUNDARIES.

    - C. POLE COALESCENCE

DISTANCE BETWEEN POLES BECOMES SMALL.

POLES BECOME BRANCH-CUT.



        1. BEST IN LONG DEVICES
        2. NOTE: STEP AND IMPULSE RESPONSES DIFFER AND ARE NO LONGER EXPONENTIAL
            - A. STEP ERFC $(\sqrt{t/\tau})$
            - B. PULSE $\frac{\exp(-t/\tau)}{\sqrt{t}}$

2. IGNORE "NONDOMINANT REGIONS"
    - A. SENSITIVE TO EXCITATION
        - 1. EXTERIOR EXCITATION BETTER THAN INJECTION
    - B. HELPS IF IT IS DOMINANT POLE

3. DEPLETION LAYER APPROXIMATIONS
    - A. PROBLEMS
        - 1. UNKNOWN BOUNDARY CONDITIONS
        - 2. CAPACITANCE
            - A. YIELDS EXTRA POLE (DECAY TERM) UNRELATED TO RECOMBINATION
            - B. AREA DEPENDENT, LOAD DEPENDENT
            - C. CAN BE SHUNTED WITH FORWARD CONDUCTANCE
        - 3. CONDUCTANCE
        - 4. GENERATION RECOMBINATION
    - B. ROUGH ORDERING OF SENSITIVITY TO EFFECTS

        LEAST
        - 1. DC SHORT CIRCUIT
        - 2. AC SHORT CIRCUIT
        - 3. DC OPEN CIRCUIT
        - 4. AC OPEN CIRCUIT

        MOST

4. KNOWN STRUCTURE

5. LIGHT MEASUREMENTS REQUIRE ABSORPTION COEFFICIENTS
   EXCEPTION: PENETRATING RADIATION

6. SIMPLE RECOMBINATION
    - A. LOW INJECTION
    - B. SINGLE RECOMBINATION LEVEL
    - C. LOW PROBABILITY OF OCCUPATION
    - D. LEVEL NEAR MIDGAP

7. SIMPLE STRUCTURE & CONSTANT KNOWN PHYSICAL PARAMETERS
    - A. CONSTANT τ μ
    - B. KNOWN μ
    - C. NO DRIFT FIELDS
    - D. NO BAND GAP NARROWING
    - E. ZERO OR INFINITE RECOMBINATION VELOCITIES

Recombination Parameter Gradients and Nonclassical Mobility References

Measurement of Diffusion Length Gradients in Hydrogen Passivated Silicon R.H. Michaels 1984 Appl. Phys. Lett., 46 415 (1985).

Measurement of Carrier Lifetime Profiles in Diffused Layers of Semiconductors B.J. Baliga and Michael S. Adler IEEE ED-25, 472 (1978).

The Use of Spatially-Dependent Carrier Capture Rates for Deep-Level Defect Transient Studies G.P Li and K.L. Wang SSE 26, 825 (1983).

Photogenerated Carrier Collection in Semiconductors with Low Mobility-Lifetime Products F. Galluzzi J Phys D. Appl Phys, 18 685 (1985).

Measurement of Minority Carrier Drift Mobility in Solar Cells Using a Modulated Electron Beam, S. Othmer and M.A. Hopkins NASA CP-2169 pp 61-66, 1980.

Effective Lifetimes in High Quality Silicon Devices, D.K. Schroder SSE 27, 247 (1984).

Second Generation

REQUIREMENTS

1. MEASURE MULTIPLE PARAMETERS
2. ACCOUNT FOR COMPLEX DEVICE BEHAVIOR, MULTIREGION NONUNIFORMITY, DRIFT FIELDS, BGN, JUNCTION

MULTIPLE UNKNOWNS: DETERMINATION REQUIRES MULTIPLE DATA

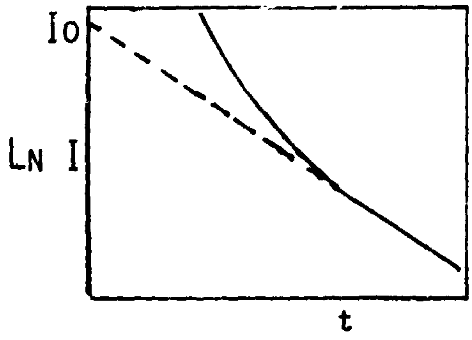
TWO SOURCES

1. TWO PIECES OF DATA FROM SINGLE RESPONSE
   - A. EIGENVALUE, EIGENVECTOR
     - I. SCCD
   - B. REAL PART, IMAGINARY PART
     - I. MLM
     - II. IMPEDANCE
2. VARY EXTERNAL PARAMETERS
   - A. HIGHER ORDER POLES CONTAIN INFORMATION ABOUT NONDOMINANT REGIONS AND s & μ
   - B. RESOLVE POSITION/SHAPE OF HIGHER ORDER POLES/EIGENMODES BY THE VARIATION OF EXTERNAL PARAMETERS

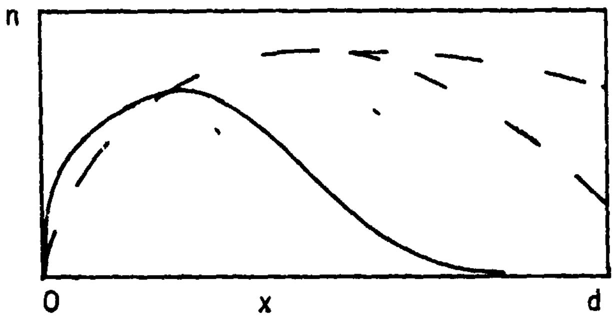
RESOLUTION SENSITIVITY AND UNIQUENESS MUST BE CONSIDERED

IN GENERAL: THE MORE VARIABLE PARAMETERS, THE MORE RESOLUTION AND SENSITIVITY

SCCD



- SLOPE AT t = LARGE IS FIRST POLE OR EIGENVALUE
- $Io = -qD\frac{d}{dx}\int_{o}^{d} n(o)\underset{\substack{\uparrow\\ \text{FIRST EIGENMODE}}}{\phi_1}('x)dx$



Three Variable Parameters Identified as Useful

1. SPATIALLY VARYING EXCITATION
    - A. DIFFERENT MINORITY CARRIER DISTRIBUTIONS
    - B. VARIES DEGREE OF EXCITATION OF PARTICULAR EIGENMODE. REGION AND DEPTH RESOLUTION
    - C. ASLBIC, MLM
2. TIME VARYING EXCITATION
    - A. MODULATION FREQUENCY OR FREQUENCY CONTENT (PULSE EXCITATION) VARIED
    - B. CONTRIBUTION OF POLE TO RESPONSE IS INCREASED AS ASSOCIATED KNEE FREQUENCY IS PASSED
    - C. MLM, CAPACITANCE CONDUCTANCE
3. VARYING BOUNDARY CONDITION
    - A. BIAS AT JUNCTION OR SURFACE
    - B. SHAPE OF EIGENMODE AND POSITION OF EIGENVALUE CHANGES
    - C. B.H. ROSE Isc & Voc DECAY; POSSIBLY MLM

Multiparameter Multiregion Measurements

METHOD	EXCITATION	MEASURED QUANTITY	VARIED PARAMETERS	NUMBER OF MEAS QUANT. PLUS 2 TIMES NUMB OF VAR. PAR.	REFERENCE
Isc-Voc PHOTO-DECAY	PENETRATING LIGHT	TIME DEPENDENT CURRENT OR JUNCTION VOLTAGE	BOUNDARY CONDITIONS	2	B.H. ROSE H.T. WEAVER J. APPL PHYS 238 54 (1983)
PHOTO-COND. DECAY	PENETRATING LIGHT	INTEGRATED CONDUCTIVITY AT TWO TIMES DURING SQUARE PULSE RESPONSE	NONE	2	S. ERÄNEN M. BLOMBERG J APPL. PHYS. 2372 (1984)
CAPACITANCE CONDUCTANCE	INJECTION	DYNAMIC DIFFUSION CAPACITANCE & CONDUCTANCE	FREQUENCY (BOUNDARY CONDITIONS)	4 (6)	A. NEUGROSHEL ET. AL. IEEE TRANSACTIONS ED-24 485 (1978)
SCCD	INJECTION	STEADY STATE & TIME DEPENDENT CURRENT	NONE	2	TOE-WON JUNG ET. AL. IEEE TRANSACTIONS ED-31 588 (1984)
ASLBIC	LIGHT	STEADY STATE CURRENT	WAVELENGTH	2	M. WOLF ET. AL. 17 PHOTOVOLTAIC SPECIALISTS CONF. 1984
EBIC	ELECTRON BEAM	STEADY STATE CURRENT	ENERGY	2	L.D. PARTAIN ET. AL. 17 PHOTOVOLTAIC SPECIALISTS CONF. 1984
SMLM	MODULATED LIGHT	MODULATED CURRENT (VOLTAGE) MAGNITUDE & PHASE	FREQUENCY WAVELENGTH (BOUNDARY CONDITIONS)	6 (8)	M. NEWHOUSE JPL CONTRACT 956290 REPORTS

Range of Poles

short circuit $1/\tau + \frac{D}{d^2}\frac{\Pi}{2}$ minimum

$1/\tau + \frac{D}{d^2}\Pi$ maximum

open circuit $1/\tau$ minimum

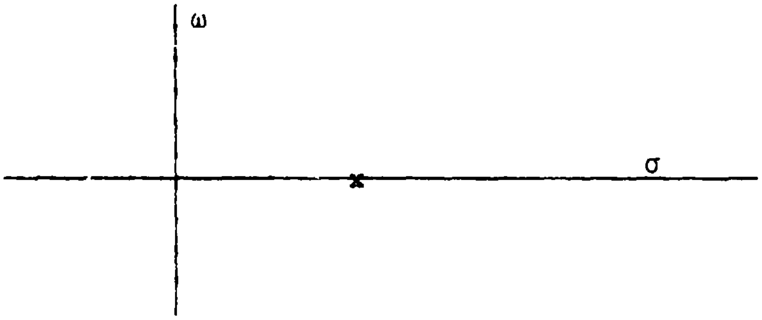
$1/\tau + \frac{D}{d^2}\frac{\Pi}{2}$ maximum

exact value determined by $\frac{sd}{D}$

$\therefore$ problems when $\frac{D}{d^2} >> 1/\tau$

or

$\frac{1}{d^2} >> 1/L^2$



then pole position determined by s, d, D and not by τ

Not solved with AC $\frac{L}{\sqrt{1 + i\omega\tau}}$

Proof

d.C

$$n(x,t) = \int_0^d \sum_m \frac{\phi_m^2(x)}{\frac{D}{d^2} C + \frac{1}{\tau}} h(x)dx$$

$$= \int_0^d \sum_m \frac{\phi_m^2\ (x) \qquad h(x)/D}{\frac{c}{d^2} + 1/L^2} dx$$

$\therefore$ if $L \gg \frac{d}{c}$ than

$$\approx \int_0^d \sum_m \frac{\phi_m^2(x)h(x)/D}{\frac{c}{d^2}} dx$$

No L dependence

for a.c. $L^* = L/\sqrt{1 + i\omega\tau}$

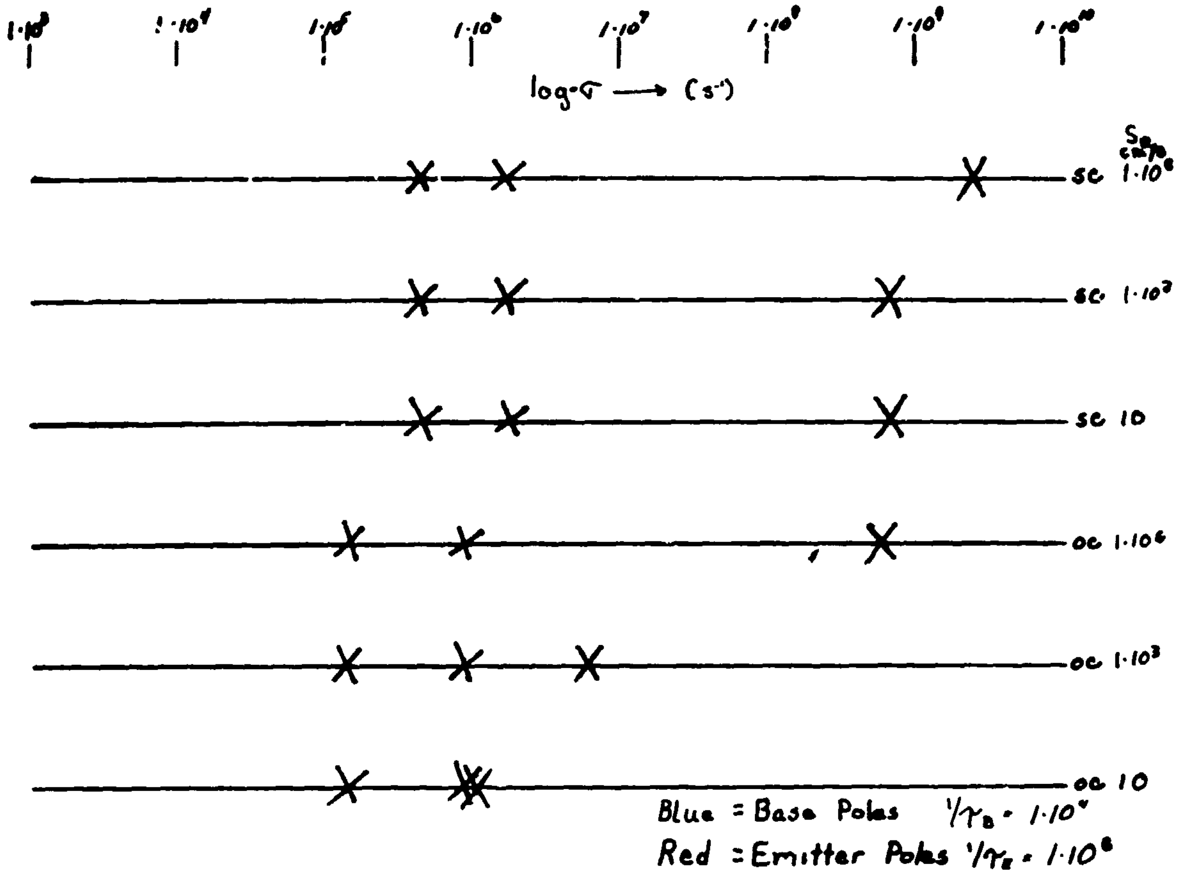
$$n(x,t) = \int_0^d \sum_m \frac{\phi_m^2(x)h(x)/D}{\frac{c}{d^2} + \frac{1 + i\omega\tau}{L^2}} dx$$

$$= \int_0^d \sum_m \frac{\phi_m^2(x)h(x)/D}{\frac{c}{d^2} + \frac{1}{L^2} + \frac{i\omega}{D}} dx$$

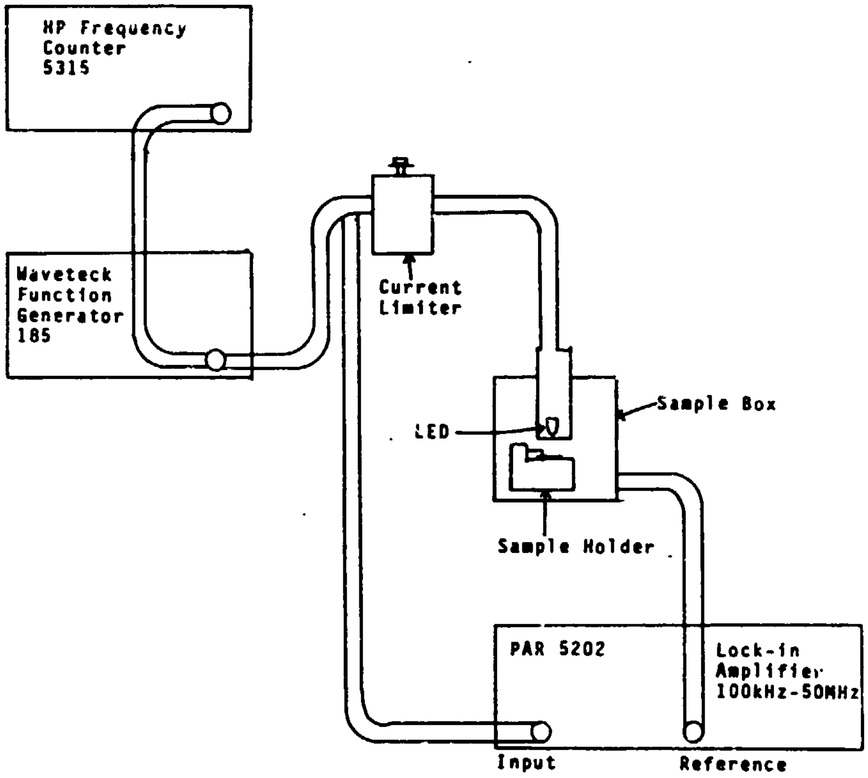
if $L \gg \frac{d}{c}$ than

$$\approx \int_0^d \sum_m \frac{\phi_m^2(x)h(x)/D}{\frac{c}{d^2} + \frac{i\omega}{D}} dx$$

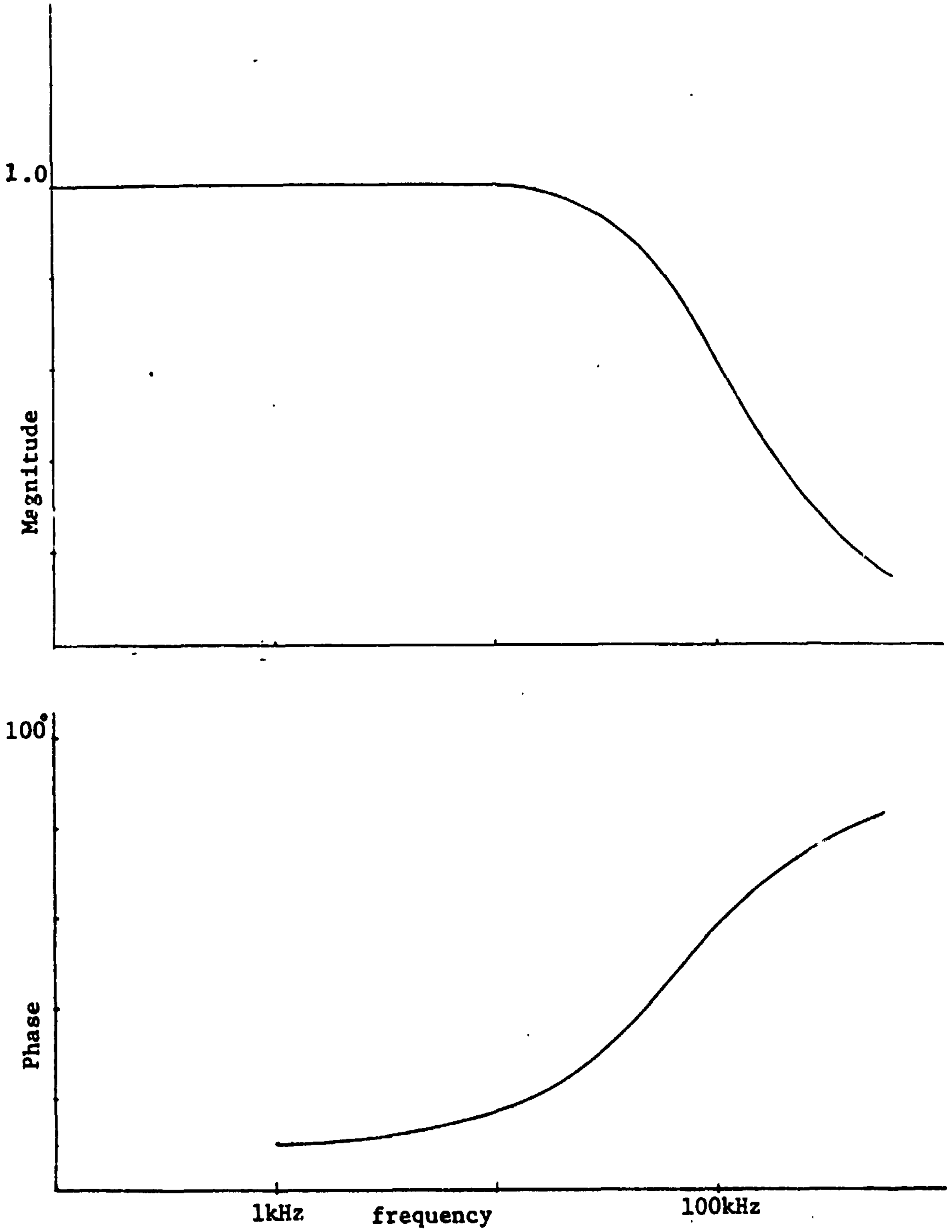
Still no L dependence


1·10^3
1·10^4
1·10^5
1·10^6
1·10^7
1·10^8
1·10^9
1·10^10
log σ → (s^-1)
S_e cm/s
sc 1·10^6
sc 1·10^3
sc 10
oc 1·10^6
oc 1·10^3
oc 10
Blue = Base Poles 1/τ_B = 1·10^4
Red = Emitter Poles 1/τ_E = 1·10^8

Ortec 9505 Lock-in Amplifier, 10-200 kHz



MLM Data



MLM Junction Capacitance

- FULL SIZED DEVICES HAVE .1 TO .5 μF JUNCTION CAPACITANCE
- WITH 10Ω LOAD RC ∼ 30 TO 160 KHz
- INFLUENCE IDENTIFIED WITH REVERSE BIAS EFFECT ON 3DB POINT
- SOLUTION: REDUCE AREA AND LOAD RESISTANCE, MEASURE AND ACCOUNT FOR EFFECT, WORK AT OPEN CIRCUIT WITH BIAS LIGHT

Summary

- UTILIZED MODEL TO FORMULATE PROBLEM
- REVIEWED CLASSICAL METHOD CLASSIFYING AND IDENTIFYING LIMITING ASSUMPTIONS AND SIMPLIFICATIONS
- IDENTIFIED AND ANALYZED TECHNIQUES REQUIRED FOR EXTENSION OF CLASSICAL METHODS FOR MULTIPARAMETER MULTIREGION MEASUREMENT
- CONSIDERED IMPLICATIONS FOR THIN REGIONS
- BUILT MODULATED LIGHT MEASUREMENT FACILITY AND MADE MEASUREMENTS SHOWING THE LARGE EFFECTS OF JUNCTION CAPACITANCE

Future

- A MORE COMPLETE EXPERIMENTAL EVALUATION OF SMLM
- AN ANALYTICAL TREATMENT TO HELP RIGOROUSLY DECONVOLVE MULTIPOLE, MULTIPARAMETER AND MULTIREGION DATA
- COMPUTER SIMULATIONS TO EMPIRICALLY EVALUATE ANALYTICAL TECHNIQUES AND MODEL MULTIPARAMETER, MULTIREGION, DRIFT FIELD AND BAND GAP NARROWING EFFECTS
- USE ANALYSIS AND SIMULATIONS TO ADDRESS QUESTIONS OF RESOLUTION, SENSITIVITY AND UNIQUENESS