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HIGH-EFFICIENCY SILICON SOLAR CELLS

UNIVERSITY OF WASHINGTON

Larry C. Olsen

ORGANIZATION: JOINT CENTER FOR GRADUATE STUDY (UNIVERSITY OF WASHINGTON)

PRINCIPAL INVESTIGATOR: DR. LARRY C. OLSEN

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OTHER CONTRIBUTORS: DR. BILL ADDIS
DR. WES MILLER
GLEN DUNHAM
ERIC EICHELBERGER
DAN DOYLE

Objectives and Approach

OBJECTIVES

- ACHIEVE AN AMI EFFICIENCY > 19%.
- IDENTIFY LIMITING CURRENT MECHANISMS FOR HIGH EFFICIENCY CELLS.
- INVESTIGATE APPROACHES FOR PASSIVATING SURFACES OF SILICON SOLAR CELLS.

APPROACH

SILICON MINP SOLAR CELLS

- INCREASE J_{PH} TO 36 mA/cm² WITH TiO_x/MgF_2 DBLAR AND BY USING COLLECTOR GRID WITH 4% SHADOWING.
- OPTIMIZE EMITTER DONOR CONCENTRATION PROFILE TO MINIMIZE CURRENT LOSSES.

CURRENT LOSS MECHANISMS

- CONDUCT TEMPERATURE-DEPENDENT I-V ANALYSES TO IDENTIFY CURRENT LOSS MECHANISMS.
- MODELING CALCULATIONS FOR INTERPRETING EXPERIMENTAL RESULTS.

SURFACE PASSIVATION

- INVESTIGATE PECVD SiN_x FOR PASSIVATION OF SILICON.
- DETERMINE SURFACE RECOMBINATION VELOCITY FROM PHOTORESPONSE.
- DETERMINE D_{ss} FROM CAPACITANCE MEASUREMENTS ON HIGHLY DOPED N-TYPE WAFERS AND ON N^+ SURFACES OF N^+/P CELLS.

Surface Passivation Studies

SURFACE STATE DENSITY

DETERMINE D_{SS} FROM HIGH FREQUENCY AND SLOW RAMP MEASUREMENTS WITH Al GATES.

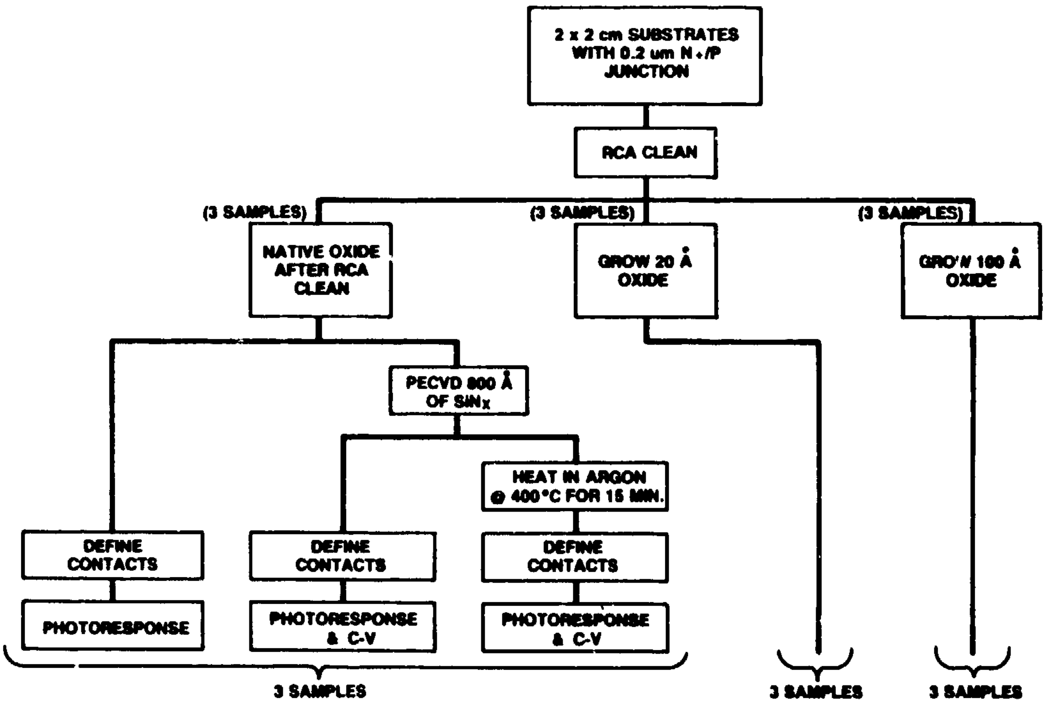
- **2 ohm-cm (N_A = 7x10^{15} cm^{-3}) P-TYPE**
- **0.2 ohm-cm (N_A = 2x10^{17} cm^{-3}) P-TYPE**
- **.08 ohm-cm (N_D = 7x10^{17} cm^{-3}) N-TYPE**
- **.01 ohm-cm (N_D = 5x10^{18} cm^{-3}) N-TYPE**

MODIFIED ROSIER MEASUREMENT

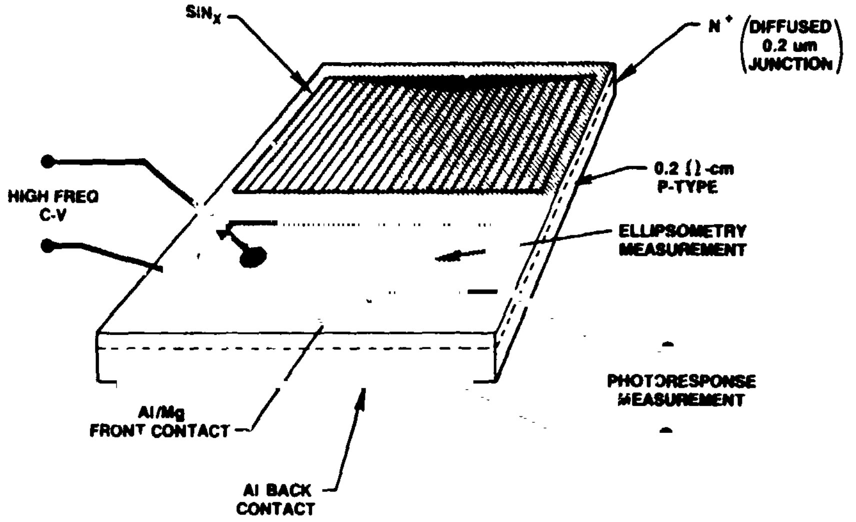
FABRICATE DEVICE STRUCTURE WITH SiN_x DEPOSITED ONTO DIFFUSED N^+/P JUNCTIONS WHICH ALLOWS MEASUREMENTS OF:

- **D_{SS} FROM HIGH FREQUENCY C-V APPLIED TO N^+ SURFACE.**
- **SURFACE RECOMBINATION VELOCITY FROM PHOTORESPONSE.**

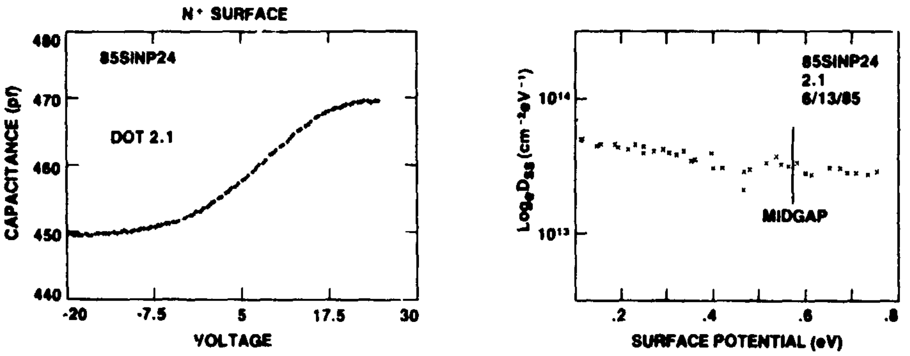
Processing Outline for Recombination Study



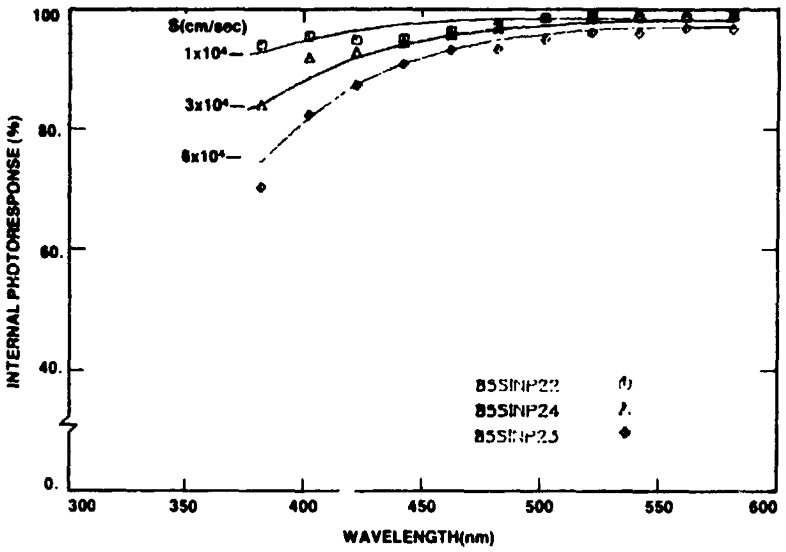
Device Structure for Surface Recombination Study



Modified Rosier Measurements: Density of States on Surface of n$^+$/p Cell



Internal Photoresponse vs Wavelength



Surface Recombination Studies

SAMPLE	OXIDE THICKNESS (Å)	SIN_X THICKNESS (Å)	ANNEAL OF SIN_X	S (cm/sec)	D_{SS} ($cm^{-2}eV^{-1}$)
85-15	NATIVE	——	——	$1.0x10^5$	——
85-17	NATIVE	890	——	$5.5x10^4$	$2.5x10^{13}$
85-16	NATIVE	820	H.T.	$2.0x10^4$	$2.5x10^{13}$
85-24	20 Å	——	——	$3.0x10^4$	——
83-23	20 Å	1020	——	$6.0x10^4$	$2.5x10^{13}$
85-22	20 Å	1030	H.T.	$1.0x10^4$	$2.4x10^{13}$
85-20	100 Å	——	——	$8.0x10^3$	——
85-19	100 Å	950	——	$4.0x10^4$	$2.5x10^{13}$
85-18	100 Å	1020	H.T.	$9.0x10^3$	$2.4x10^{13}$

NOTES: H.T. REFERS TO HEAT TREATMENT AT 400°C FOR 15 MINUTES.

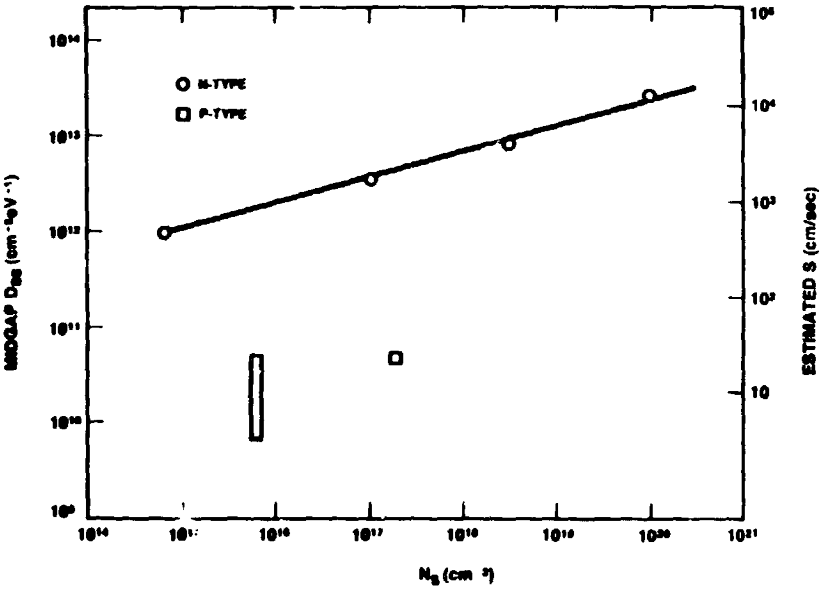
Variation of Surface State Density With Dopant Concentration

SAMPLE RESISTIVITY (ohm-cm)	DOPANT CONCENTRATION (cm^{-3})	D_{SS} ($cm^{-2}eV^{-1}$) DEPOSITED	D_{SS} ($cm^{-2}eV^{-1}$) AFTER H.T	ESTIMATED SURFACE RECOMB VELOCITY (cm/sec)
2.0 P-TYPE	7×10^{15}	5×10^{11}	$< 5 \times 10^{10}$	25
0.2 P-TYPE	2×10^{17}	5×10^{11}	5×10^{10}	25
7.0 N-TYPE (P-DOPED)	7×10^{14}	1.7×10^{12}	1.0×10^{12}	500
.08 N-TYPE (Sb-DOPED)	1.3×10^{17}	3×10^{12}	3×10^{12}	1.5×10^{3}
.01 N -TYPE (Sb-DOPED)	3.0×10^{18}	8×10^{12}	8×10^{12}	4.1×10^{3}

NOTES: (1) MEASUREMENTS ON 'MOS' STRUCTURES BASED ON PECVD SiN_x ON HOMOGEOUSLY DOPED WAFERS.

(2) H.T. REFERS TO 40 MINUTES AT 450°C IN ARGON.

(3) ESTIMATED SURFACE RECOMBINATION VELOCITY BASED ON $\sigma = 10^{-15} cm^2$.



NOTE: ESTIMATED S BASED ON $\sigma = 10^{-15} cm^2$.

Effect of Illumination on I-V Parameters

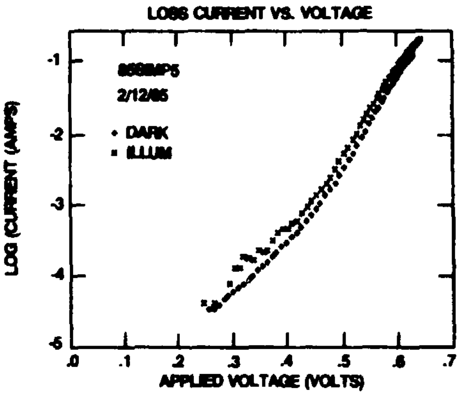
DARK CHARACTERISTICS

$n = 1.00$

$J_O = 2.1 \times 10^{-12}$ A/cm²

$\phi = 1.04$ eV

DOMINANT LOSS MECHANISM:
EMITTER RECOMBINATION



ILLUMINATED CHARACTERISTICS

$n = 1.10$

$J_O = 4.0 \times 10^{-11}$ A/cm²

$\phi = 1.01$ eV

DOMINANT LOSS MECHANISM:
DEPLETION LAYER RECOMBINATION

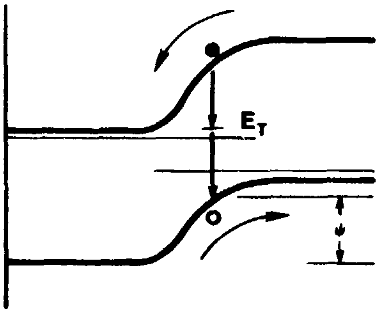
POSSIBLE TRAP CHARACTERISTICS:
$E_C - E_T \simeq 0.2$ eV $N_T \simeq 10^{17}$ cm^{-3}

Depletion Layer Recombination Revisited

THEORY

$$J_R = \int_0^W R(x)\,dx = \int_0^W \frac{R(\psi)\,d\psi}{\frac{d\psi}{dx}}$$

R ≡ Shockley - Read - Hall Expression For Recombination Rate

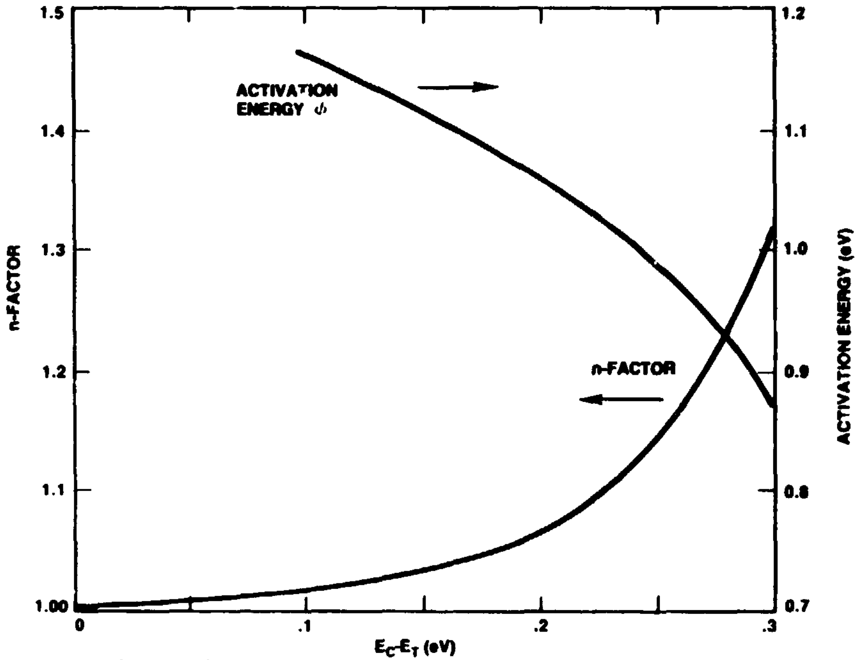


MODELING CALCULATIONS

$$J_R = J_{OR} \exp\left(\frac{V}{nkT}\right) \quad V >> kT$$

$$J_{OR} = J_{OO} \exp\left(-\frac{\phi}{kT}\right)$$

Modeling Calculations for Depletion Layer Recombination



$N_A = 2x10^{17}$ cm $^{-3}$
$\tau_{\ell} / \tau_{\mu} = 1$
φ DEFINED BY: $J_{OR} = J_{OO} \exp(-\phi/_{kT})$

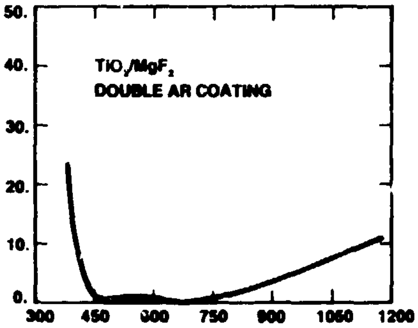
Short-Circuit Current Improvement

OBJECTIVE

- **POLISHED, 0.2 Ω-cm P-TYPE SUBSTRATE L = 150 um, DBLAR of TiO_2 and MgF_2** } **J_{PH} 37.5 $\frac{mA}{cm^2}$**
- **ASSUMING 4% SHADOWING DUE TO CURRENT COLLECTOR GRID.** } **$J_{SC} = 36.0 \frac{mA}{cm^2}$**

STATUS

- **POLISHED CELL WITH SiO_X AR:**
  $J_{SC} = 32.3 \frac{mA}{cm^2}$
- **TEXTURED CELL WITH SiO_X AR:**
  $J_{SC} = 35.5 \frac{mA}{cm^2}$



CALCULATED REFLECTANCE VS WAVELENGTH

PROGRESS

- **DEVELOPED PROCEDURES FOR DEPOSITING TiO_2 AND MgF_2. ELLIPSOMETRIC MEASUREMENTS WERE USED TO OBTAIN OPTICAL CONSTANTS. CALCULATED OPTIMUM FILM THICKNESSES FOR TiO_2/MgF_2 DBLAR COATING.**
- **DEVELOPED PROCEDURES FOR DEFINING FRONT COLLECTOR GRID BY LIFTOFF OF FULL METALLIZATION THICKNESS.**
- **DESIGNED AND ACQUIRED SHADOW MASK WHICH WILL YIELD COLLECTOR GRIDS WITH 4% SHADOWING.**

Voltage Improvement

OBJECTIVE

- **FF = 0.81 and V_{OC} = 650 mV**

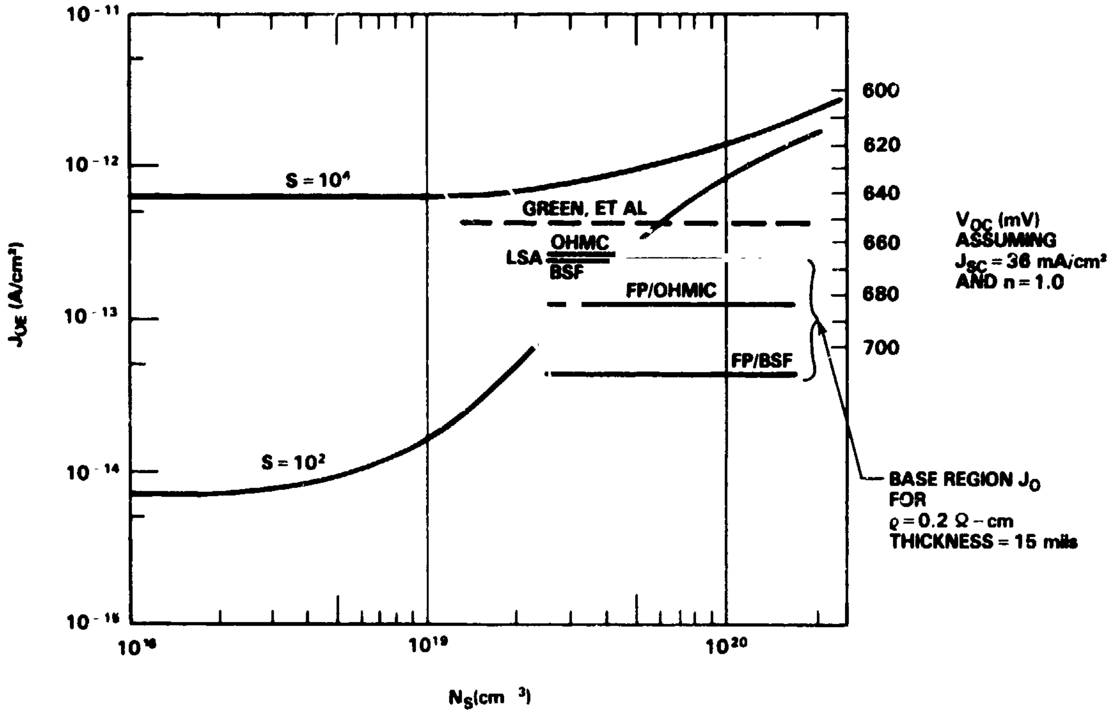
STATUS

- **FF = 0.81 and V_{OC} = 636 mV**

APPROACH

- **EMITTER OPTIMIZATION USING ION IMPLANTION:**
  $N_S \simeq 3 \text{ to } 4 \times 10^{19} \text{ cm}^{-3}$
  $R \simeq 200\ \Omega/\square$
- **REDUCTION OF SURFACE RECOMBINATION:**
  $S \simeq 10^3$ cm/sec.
- **V_{OC} = 650 mV.**
- **ASSUMING J_{SC} = 36 mA/cm², AMI EFFICIENCY = 19.0%.**

Emitter j_O vs Surface Donor Concentration



Key Results

MINP SOLAR CELLS

- DOUBLE AR COATING CONSISTING OF TiO_2/MgF_2 AVAILABLE.
- APPROACH TO MORE OPTIMUM EMITTER CONCENTRATION PROFILE
- EFFICIENCIES: 16.3%(POLISHED), 17.0%(TEXTURED)
- VOLTAGE: $V_{OC} = 636$ mV.

CURRENT LOSS MECHANISMS

- HAVE IDENTIFIED LIGHT ENHANCED CURRENT LOSS MECHANISM IN HIGH EFFICIENCY CELLS. CAN BE EXPLAINED BY DEPLETION LAYER RECOMBINATION.
- HAVE EXTENEDED Sah-Noyce-Shockley MODELING CALCULATIONS TC INCLUDE TEMPERATURE DEPENDENT I-V CHARACTERISTICS AND ENERGY ACTIVATION ANALYSIS.

SURFACE PASSIVATION

- STUDIES OF 'MOS' STRUCTURES WITH SiN_X INSULATING LAYERS ON N-TYPE WAFERS IMDICATE SURFACE STATE DENSITY CORRELATES WITH DONOR DENSITY.
- MODIFIED ROSIER MEASUREMENT DEVELOPED. INVOLVES PHOTORESPONSE ANALYSIS TO OBTAIN SURFACE RECOMBINATION VELOCITY AND HIGH FREQUENCY C-V TO OBTAIN SURFACE STATE DENSITY.
- DETERMINED THAT PECVD SiN_X ANNEALED AT 400° C RESULTS IN $S = 10^4$ cm/sec ON N^+ SURFACE WITH $N_S = 10^{20}$ cm^{-3}, SIMILAR RESULT OBTAINED WITH 100 Å SiO_2 PASSIVATION.