Georgia Tech

ECE 4813

Semiconductor Device and Material Characterization

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As with all of these lecture slides, I am indebted to Dr. Dieter Schroder from Arizona State University for his generous contributions and freely given resources. Most of (>80%) the figures/slides in this lecture came from Dieter. Some of these figures are copyrighted and can be found within the class text, *Semiconductor Device and Materials Characterization*. ***Every serious microelectronics student should have a copy of this book!***

Doping Profiling

Secondary Ion Mass Spectrometry

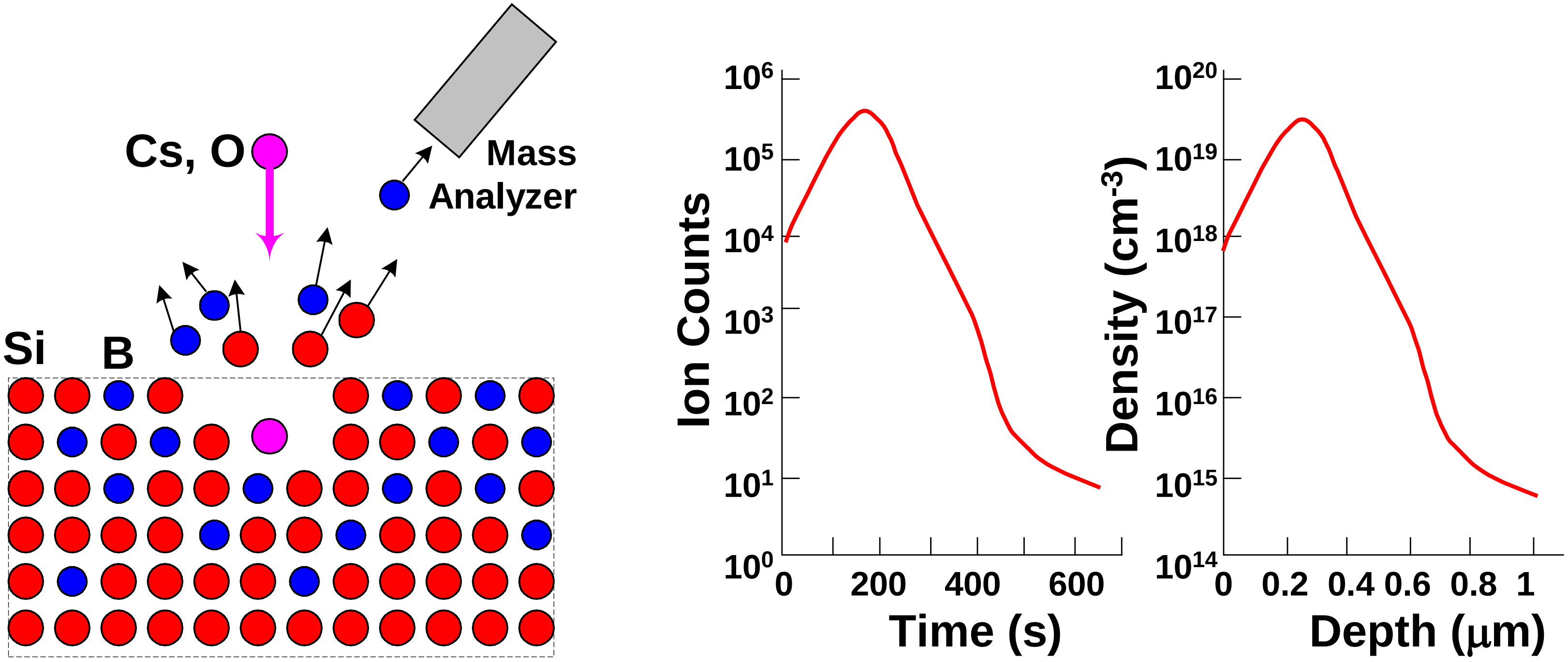
Spreading Resistance

Capacitance – Voltage

Threshold Voltage

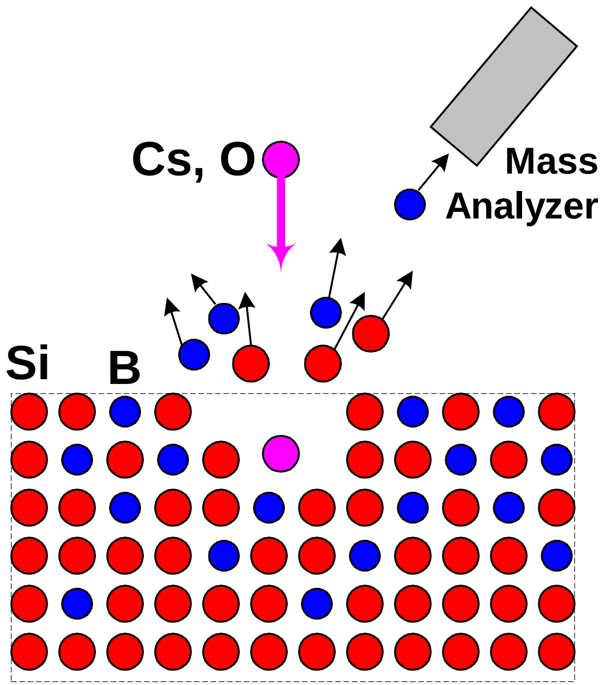
Secondary Ion Mass Spectrometry

- SIMS is the most common doping profiling technique
- Incident ions knock out atoms and ions from the substrate
- The mass of these ions is analyzed



Secondary Ion Mass Spectrometry

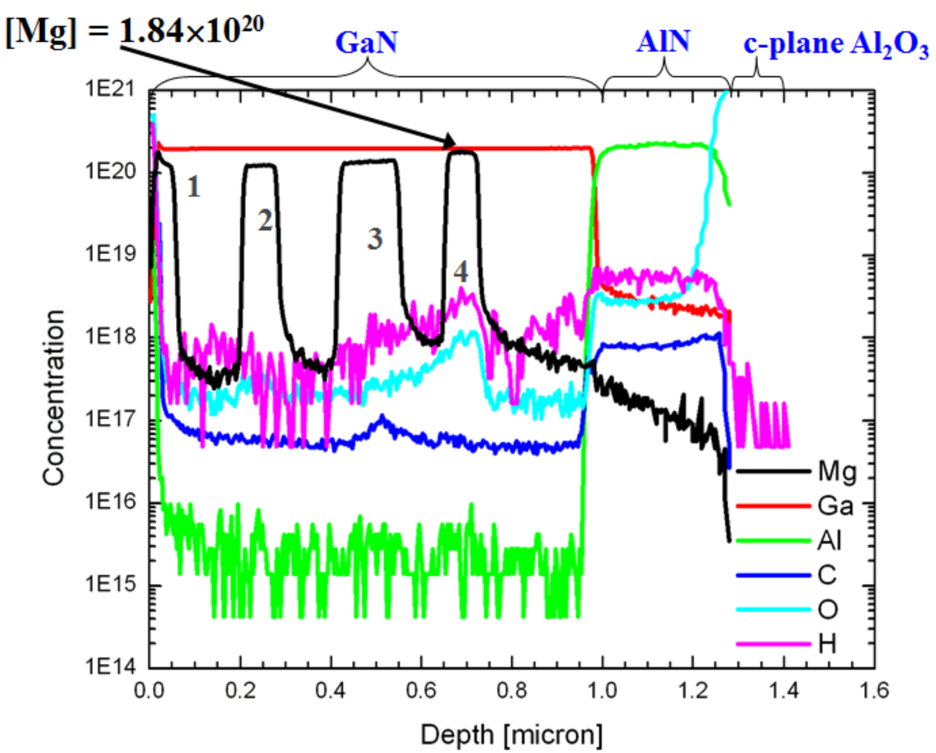
- The use of Cs or O results in a modification of the surface work function (low work function for Cs and high for O) producing either + or – ions.

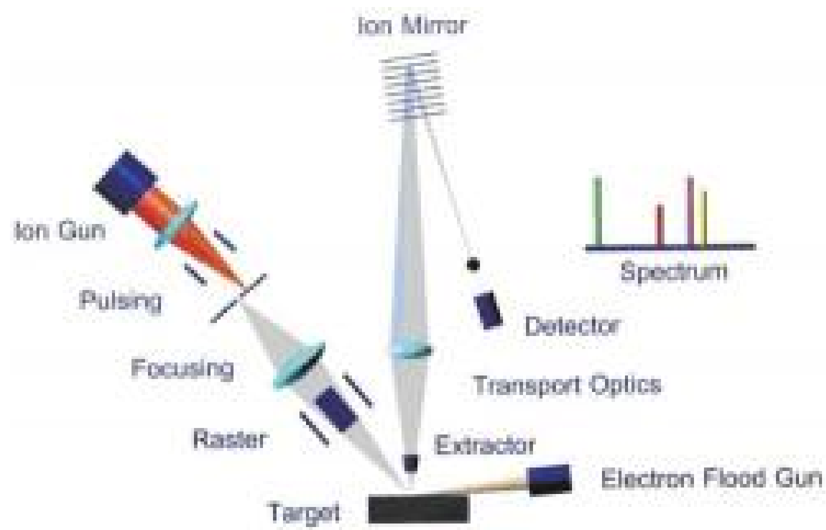


- Charging of the sample can effect both the sputter yield (changes the acceleration energy) and the focus into the mass analyzer
  - Can be offset by an electron flood gun for –ions and a +H source (rarely used) for +ions

Secondary Ion Mass Spectrometry

- Mass Spectra can be obtained
- Depth Profiling can be obtained
- Time of Flight Versions Dominate technology now

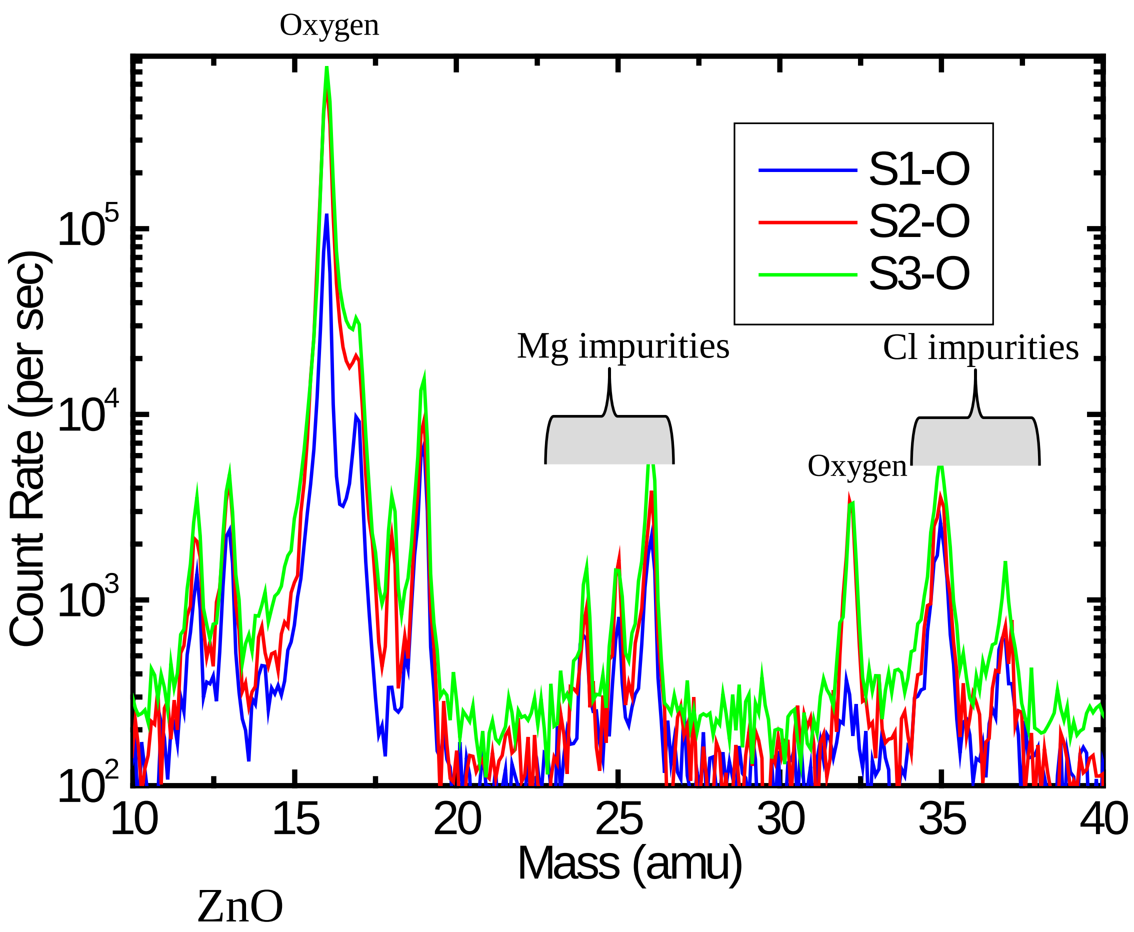




SIMS conducted by Evans Analytical Group

Secondary Ion Mass Spectrometry

- **Mass Spectra can be obtained**



Secondary Ion Mass Spectrometry

TABLE B1: Naturally Occurring Isotope Abundances(%)

Z	M	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	H	99.9	.015																		
2	He			<.01	100																
3	Li						7.5	92.5													
4	Be									100											
5	Be										19.9	80.1									
6	C												98.9	1.1							
7	N														99.6	0.37					
8	O																99.8	0.04	0.20		
9	F																			100	
10	Ne																				90.5

Z	M	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
10	Ne	0.27	9.22																		
11	Na			100																	
12	Mg				79	10	11														
13	Al							100													
14	Si								92.2	4.7	3.1										
15	P											100									
16	Si												95.0	0.75	4.2		0.02				
17	Cl															75.8		24.2			
18	Ar																0.34		0.06		99.6
19	K*																			93.3	0.01
20	Ca*																				96.9

Z	M	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
19	K*	6.7																			
20	Ca*		0.65	0.14	2.09		.004														
21	Sc					100			0.19												
22	Ti						8.0	7.3	73.8	5.5	5.4										
23	V										0.25	99.8									
24	Cr										4.35		83.8	9.50	2.36						
25	Mn															100					
26	Fe														5.8		91.7	2.2	0.28		
27	Co																			100	
28	Ni*																		68.3		26.1

Z	M	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
28	Ni*	1.1	3.6		0.91																
29	Cu			69.2		30.8															
30	Zn				48.6		27.9	4.1	18.8		0.6										
31	Ga									60.1		39.9									
32	Ge										20.5		27.4	7.8	36.5		7.8				
33	As															100					
34	Se*														0.9		9.0	7.6	23.5		49.6
35	Br*																			50.7	
36	Kr*																		0.35		2.25

Z	M	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
34	Se*		9.4																		
35	Br*	49.3																			
36	Kr*		11.6	11.5	57.0		17.3														
37	Rb					72.2		27.8													
38	Sr				0.56		9.9	7.0	82.6												
39	Y									100											
40	Zr										51.5	11.3	17.7		17.3		2.8				
41	Nb													100							
42	Mo												14.8		9.3	15.9	16.7	9.6	24.1		9.6
44	Ru*																5.5		1.9	12.7	12.6

Z	M	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120
44	Ru*	17.0	31.6		18.7																
45	Rh			100																	
46	Pd		1.0		11.4	22.3	27.3		26.5		11.7										
47	Ag							51.8		48.2											
48	Cd						1.3		0.9		12.9	12.8	24.1	12.2	28.7		7.5				
49	In													4.3		95.7					
50	Sn*												1.0		0.7	0.4	14.7	7.7	24.3	8.6	32.4
52	Te*																				0.10

Z	M	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140
50	Sn*		4.6		5.6																
51	Sb	57.3		42.7																	
52	Te*		2.6	0.91	4.8	7.1	19.0		31.7		33.8										
53	In							100													
54	Xe				0.10		0.09		1.9	26.4	4.1	21.2	26.9		10.4		8.9				
55	Cs													100							
56	Ba										0.10		0.10		2.4	6.6	7.9	11.2	71.7		
57	La																		0.09	99.9	
58	Ce*																0.19		0.25		88.5

Z	M	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160
58	Ce*		11.1																		
59	Pr	100																			
60	Nd		27.1	12.2	23.8	8.3	17.2		5.8		5.6										
62	Sm				3.1			15.0	11.3	13.8	7.4		26.7		22.7						
63	Eu											47.8		52.2							
64	Gd												0.20		2.2	14.8	20.5	15.7	24.8		21.9
65	Tb																			100	
66	Dy*																0.06		0.1		2.3

Z	M	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180
66	Dy*	18.9	25.5	24.9	28.2																
67	Ho					100															
68	Er		0.14		1.6		33.6	23	26.8		14.9										
69	Tm									100											
70	Yb								0.13		3.1	14.3	21.9	16.1	31.8		12.7				
71	Lu															97.4	2.6				
72	Hf														0.16		5.2	18.6	27.1	13.7	35.2
73	Ta*																				0.01
74	W*																				0.13

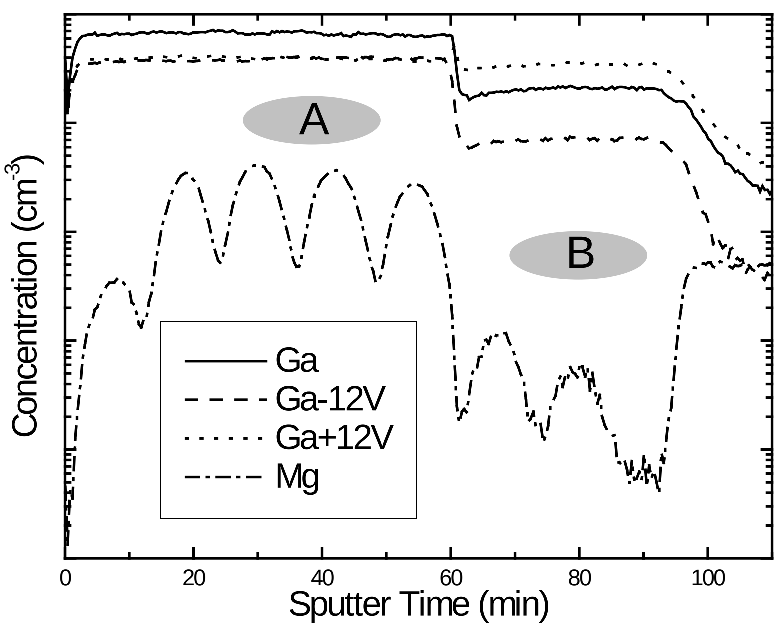
Z	M	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200
73	Ta*	100																			
74	W*		26.3	14.3	30.7		28.6														
75	Re					37.4		62.6													
76	Os				0.02		1.6	1.6	13.3	16.1	26.4		41.0								
77	Ir											37.3		62.7							
78	Pt										.01		0.79		32.9	33.8	25.3		7.2		
79	Au																	100			
80	Hg*																0.15		10.1	17.	23.1

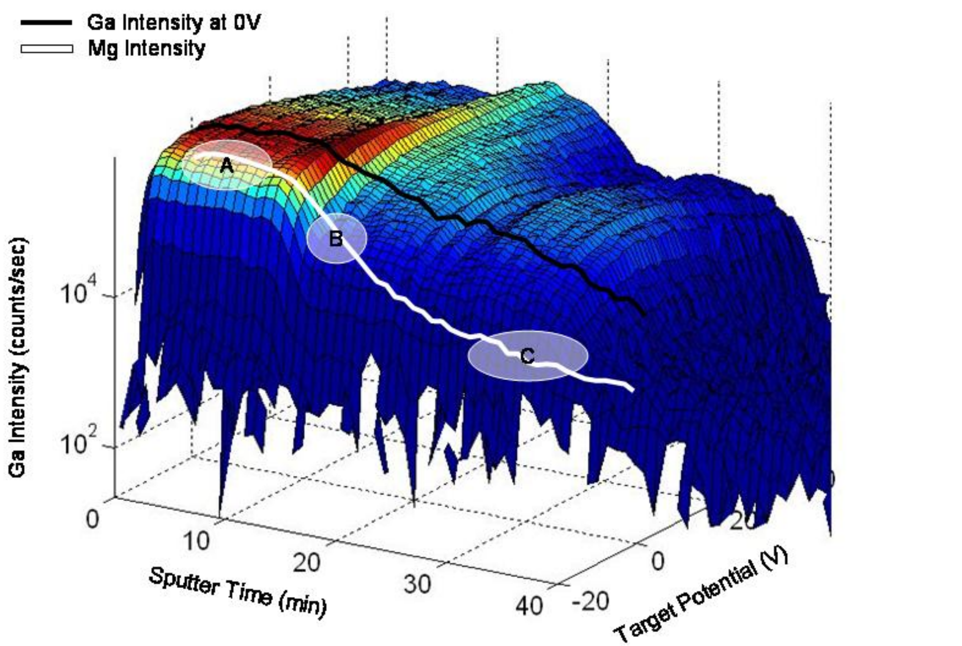
Z	M	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220
80	Hg*	13.2	29.7		6.8																
81	Tl			29.5		70.5															
82	Pb				1.4		24.1	22.1	52.4												
83	Bi									100											

Z	M	221	22	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240
90	Th												100								
92	U														.006	0.72			99.3		

Secondary Ion Mass Spectrometry

- While rarely used in simple SIMS analysis, energy spectrums for sputtered ions can tell you a great deal about the sample including in-situ resistivity analysis
- Care must be taken since SIMS often measures charge to mass ratio. Time of Flight SIMS analyzers correct this problem.

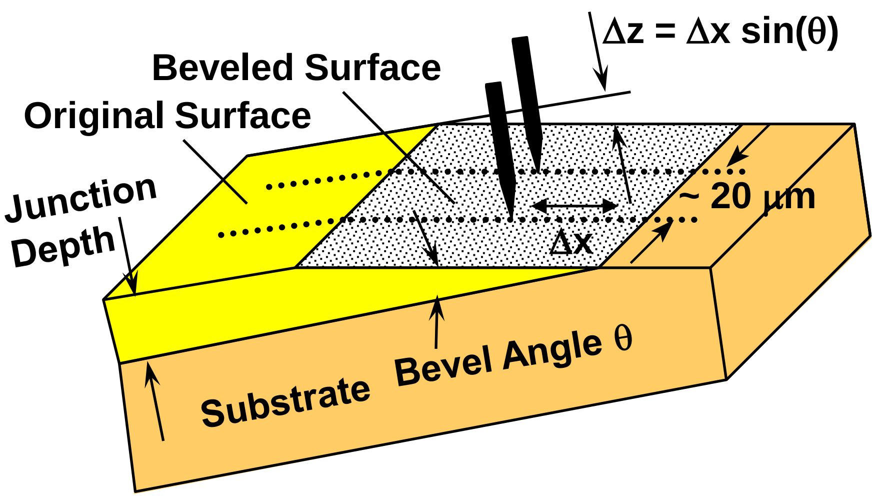


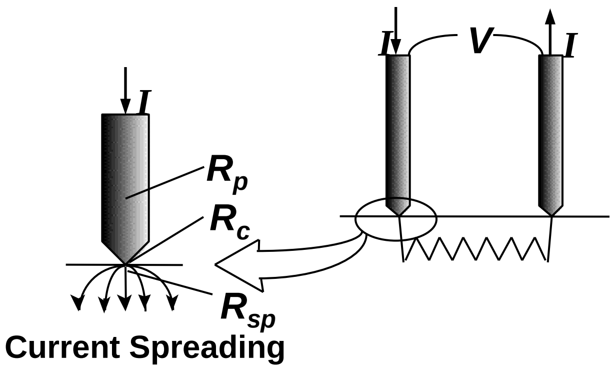


Spreading Resistance

- The wafer is bevelled extending the layer thickness
- Compare *R* to calibrated standards; R_{sp} dominates

$$R = V / I = 2R_p + 2R_c + 2R_{sp} \approx 2R_{sp}$$





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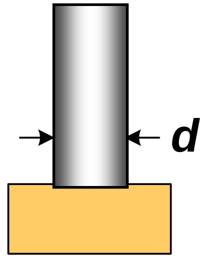
Spreading Resistance

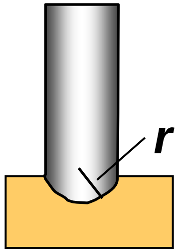
- **The spreading resistance of ideal metal-semiconductor contacts can be calculated**
  - **For flat-bottom probe of diameter *d***

$$R_{sp} = \frac{\rho}{2d}$$



  - **For hemispherical probe of radius *r***

$$R_{sp} = \frac{\rho}{2\pi r}$$



  - **For a "real" probe**

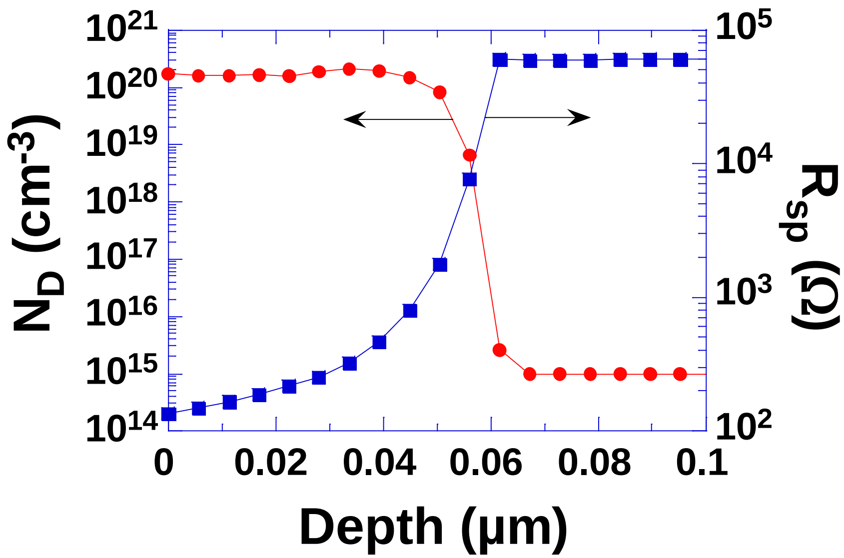
$$R_{sp} = k\frac{\rho}{2\pi r}$$

***k* must be experimentally determined**

For $\rho = 1\ \Omega$-cm,
$r = 1\ \mu$m,
$R_{sp} = 1000$-$2000\ \Omega$

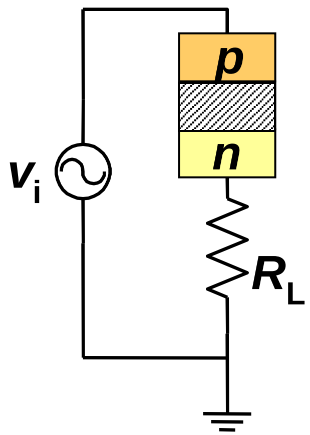
Spreading Resistance

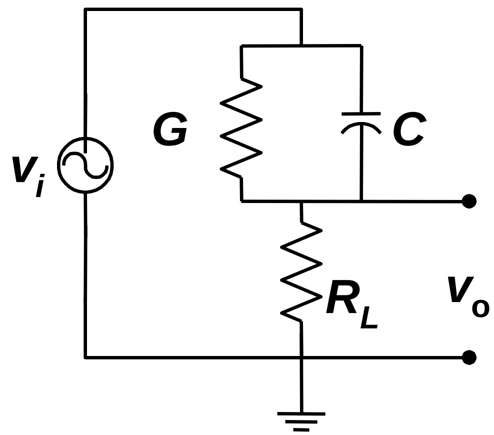
- **Spreading resistance is measured and converted to resistivity and N_A or N_D profiles**



Capacitance-Voltage

- Capacitance-voltage measurements used for
  - Doping profiling
  - Flatband voltage, oxide charge etc. in MOS devices
  - ***<u>Capacitance is a measured charge responding to a time varying voltage</u>***





$$v_o = \frac{R_L}{R_L + 1/(G + j\omega C)} v_i$$

$$\approx (G + j\omega C) R_L v_i \quad \text{for small } R_L$$

In phase:

$$v_o \approx G R_L v_i \sim G$$

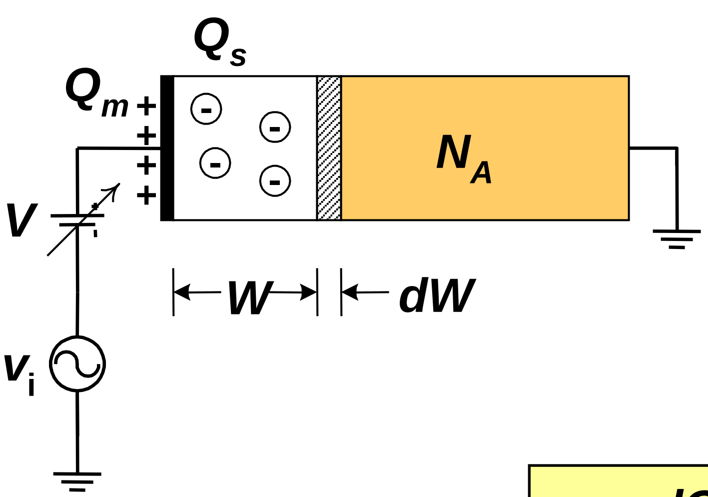
Out of phase:

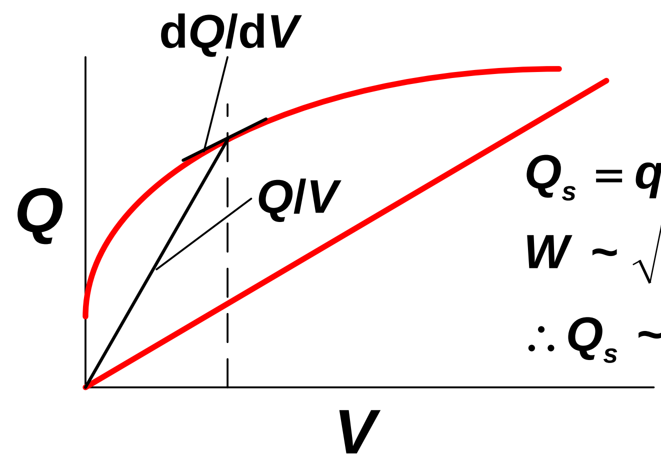
$$v_o \approx \omega C R_L v_i \sim C$$

Actual capacitance meters use ac current amps with phase-sensitive detectors to measure "in phase" and "out of phase" components.

Capacitance-Voltage

- **Need a device with a *space-charge region***
  - **Schottky diode, pn junction, MOS-C, MOSFET**
- **The dc bias, *V*, determines *W***
- **The ac bias, v_i, measures the capacitance**





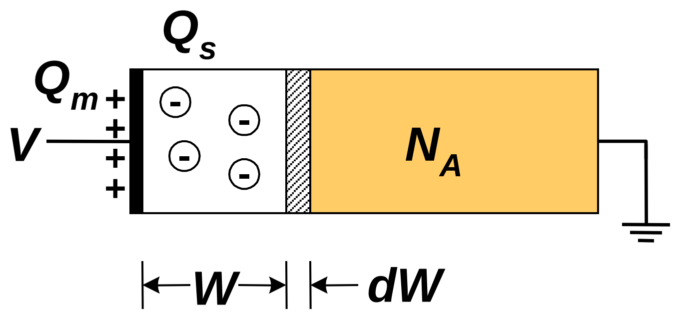
$$Q_s = qN_AW$$

$$W \sim \sqrt{V_{bi} - V}$$

$$\therefore Q_s \sim \sqrt{V_{bi} - V}$$

$$C = \frac{dQ_m}{dV} = -\frac{dQ_s}{dV}$$

Capacitance - Voltage



$$Q_s = qA\int_0^W \left(p - n + N_D^+ - N_A^-\right)dx \approx -qA\int_0^W N_A dx$$

Depletion region approximation for a p-type substrate

$$C = qA\frac{d}{dV}\int_0^W N_A dx = qAN_A(W)\frac{dW}{dV}\ (neglecting\ dN_A/dV)$$

$$C = \frac{K_s\varepsilon_o A}{W};\quad W = \frac{K_s\varepsilon_o A}{C};\quad \frac{dW}{dV} = -\frac{K_s\varepsilon_o A}{C^2}\frac{dC}{dV}$$

$$N_A(W) = -\frac{C^3}{qK_s\varepsilon_o A^2\, dC/dV} = \frac{2}{qK_s\varepsilon_o A^2\, d\left(1/C^2\right)/dV};\quad W = \frac{K_s\varepsilon_o A}{C}$$

Y-axis   X-axis

Capacitance - Voltage

- What to use?

$$N_A(W) = -\frac{C^3}{qK_s\varepsilon_o A^2\, dC/dV}$$

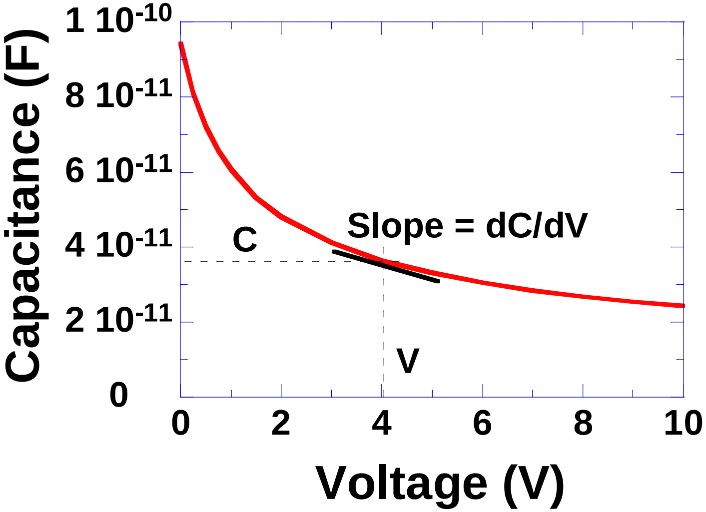
- Or

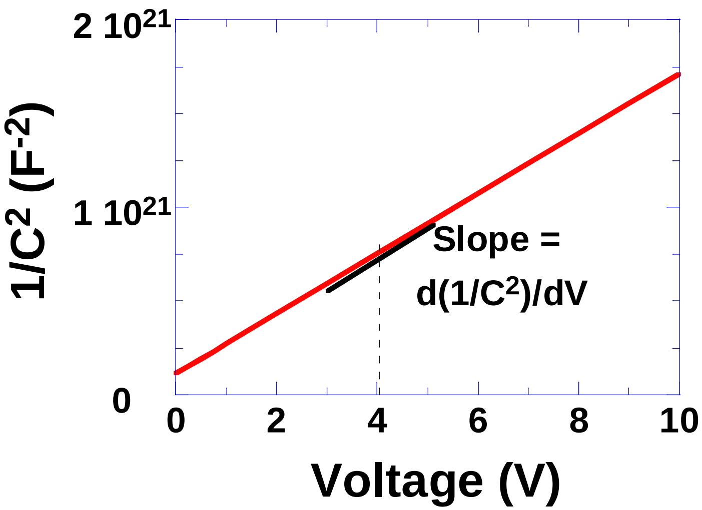
$$N_A(W) = \frac{2}{qK_s\varepsilon_o A^2\, d\left(1/C^2\right)/dV}$$

- For both

$$W = \frac{K_s\varepsilon_o A}{C}$$

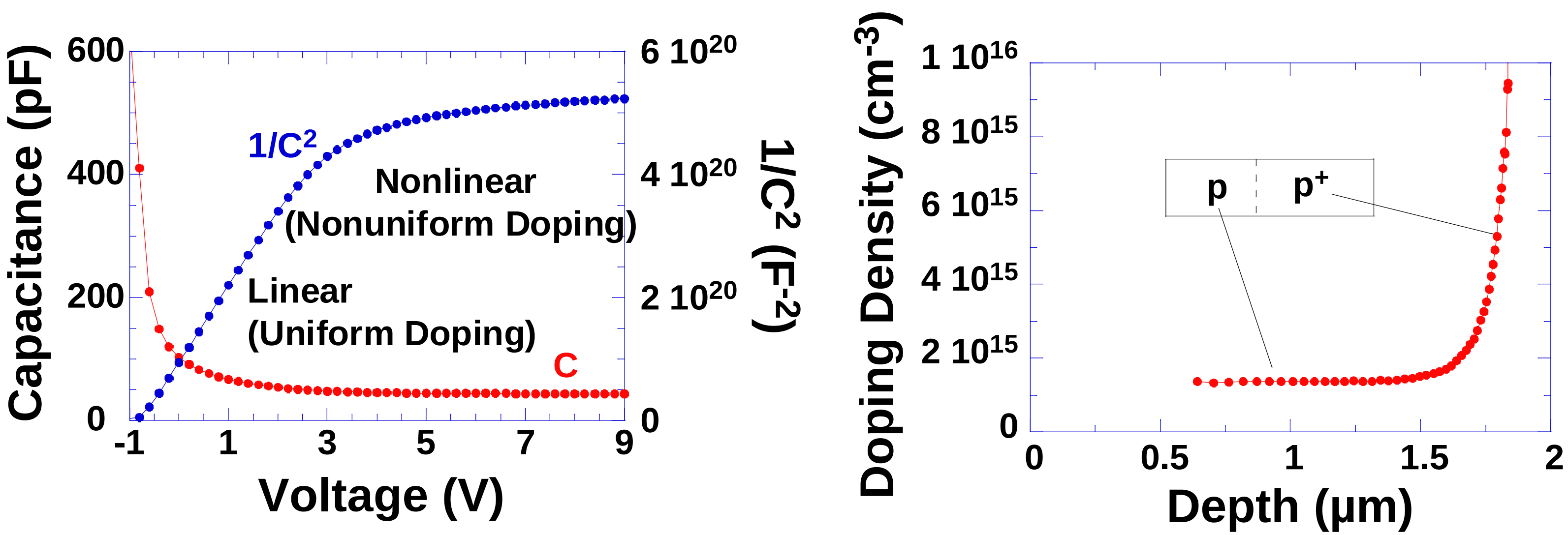
The $1/C^2 - V$ curve has less curvature!





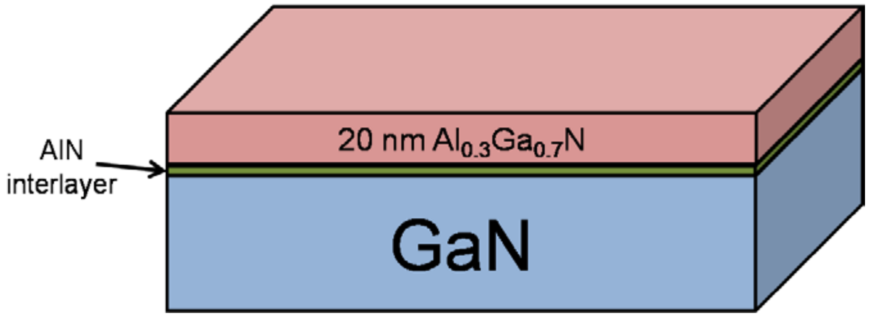
Capacitance - Voltage

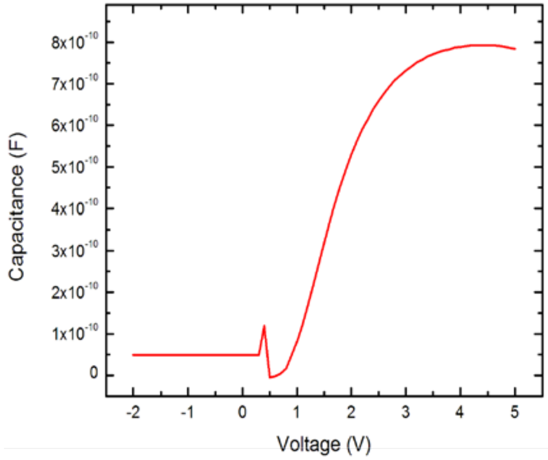
- ***C* - *V* curves are always nonlinear**
- **1/*C*² - *V* curves clearly show carrier or doping density non-uniformities**

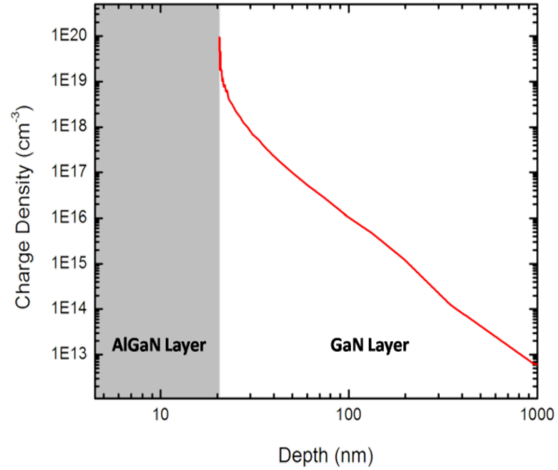


Capacitance - Voltage

- ***C* - *V* curves can determine channel depths in compound semiconductors**

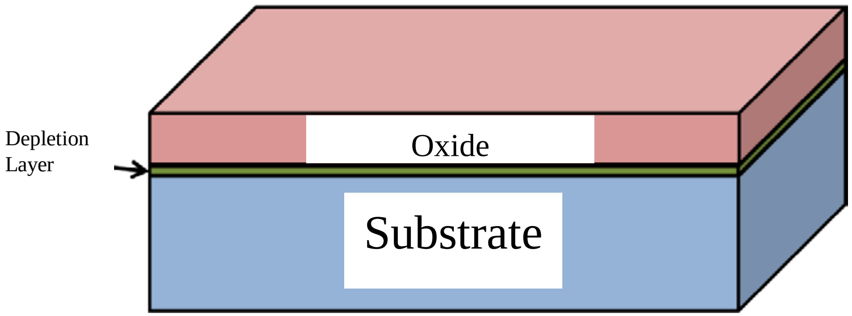


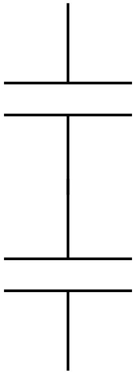




MOS Capacitance - Voltage

- ***Oxides (insulators) in series with the junctions create an additional fixed capacitor.***





$$C_{oxide} = \varepsilon A/t_{ox}$$

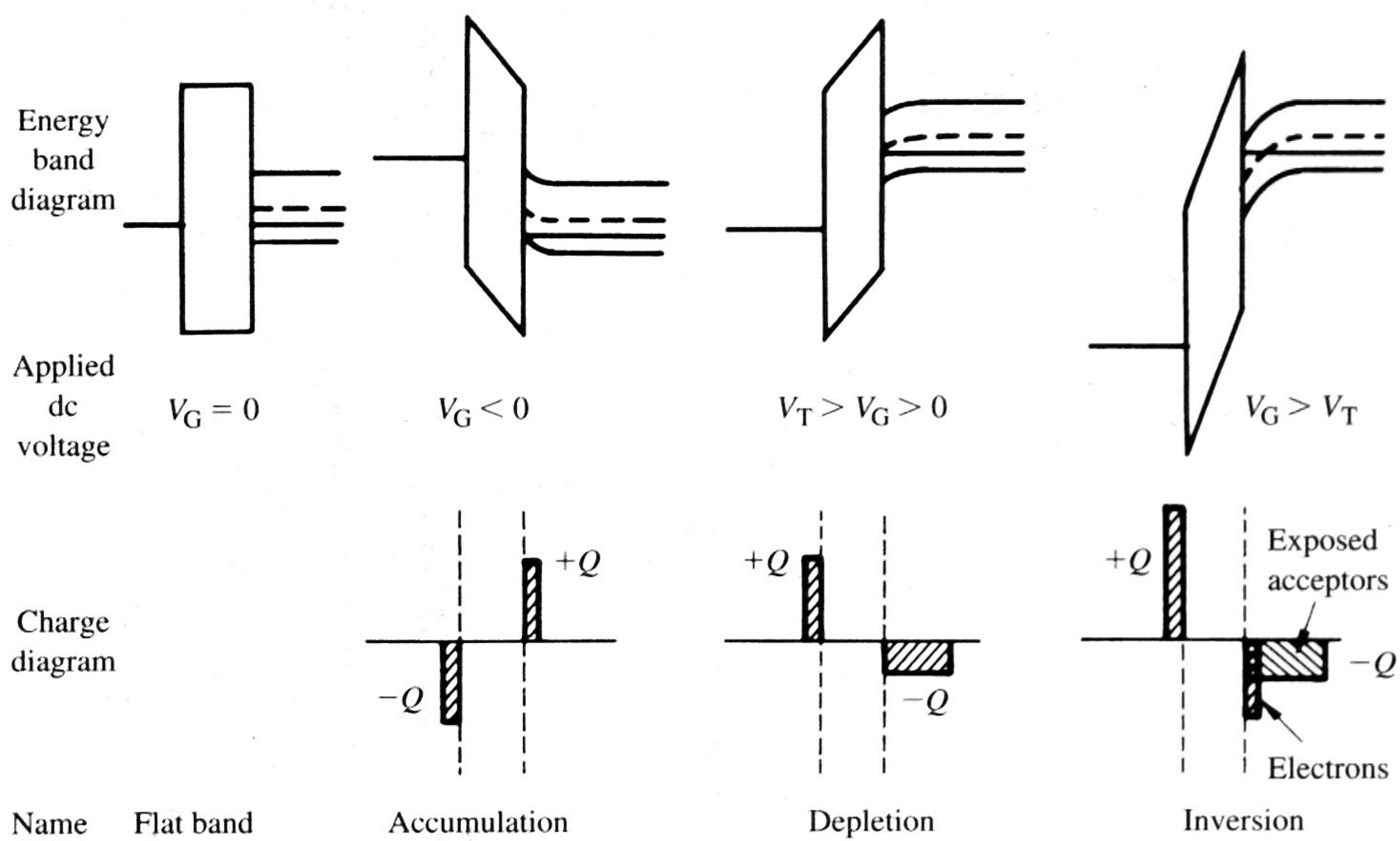
$$C = \frac{K_s \varepsilon_o A}{W}; \quad W = \frac{K_s \varepsilon_o A}{C}$$

$$x_n = \sqrt{\frac{2K_S\varepsilon_o}{q}\frac{N_A}{N_D(N_A+N_D)}(V_{bi}-V_A)} \quad and \quad x_p = \sqrt{\frac{2K_S\varepsilon_o}{q}\frac{N_D}{N_A(N_A+N_D)}(V_{bi}-V_A)}$$

$$W = x_p + x_n = \sqrt{\frac{2K_S\varepsilon_o}{q}\frac{(N_A+N_D)}{N_A N_D}(V_{bi}-V_A)}$$

$$W \sim \sqrt{V_{bi}-V}$$

MOS Capacitance

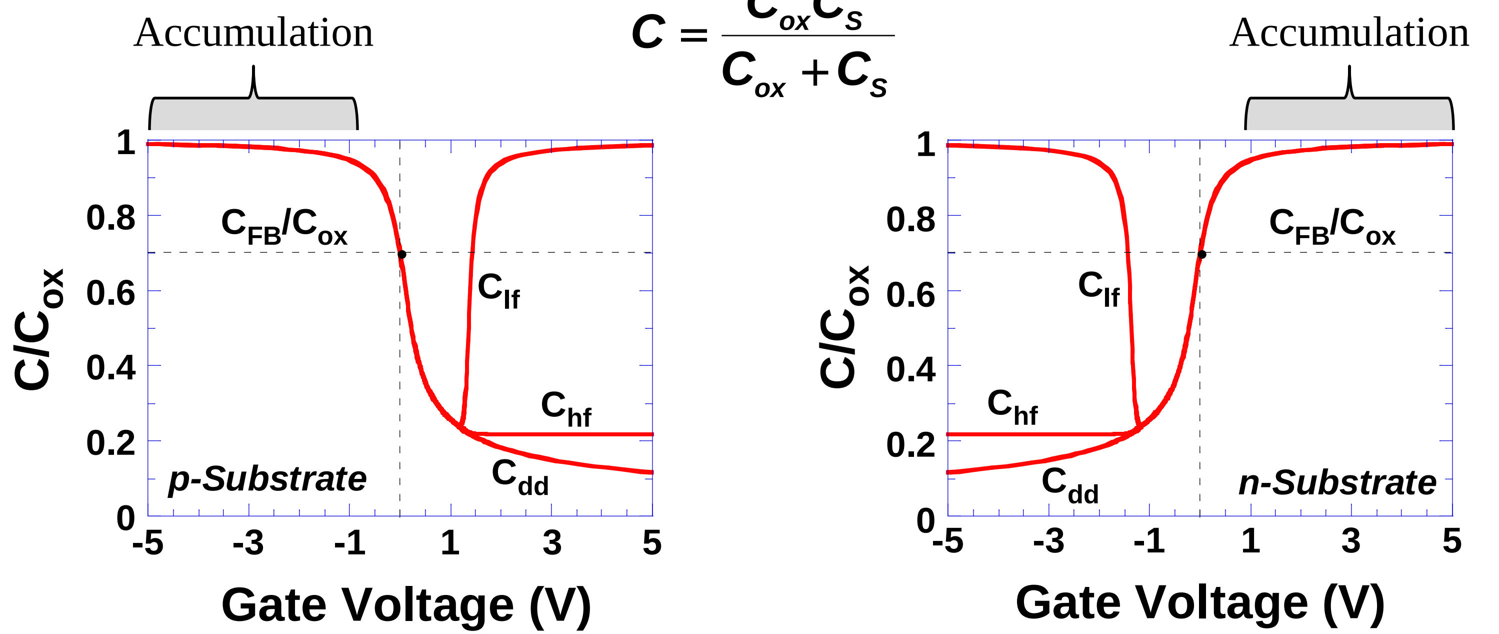


MOS Capacitance

- *Oxides (insulators) in series with the junctions create an additional fixed capacitor.*
- *Capacitance approaches the Cox in accumulation.*
- *More MOS in chapter 8…*

$$W = K_S \varepsilon_O A \left(\frac{1}{C} + \frac{1}{C_{OX}} \right)$$

$$C = \frac{C_{ox} C_S}{C_{ox} + C_S}$$



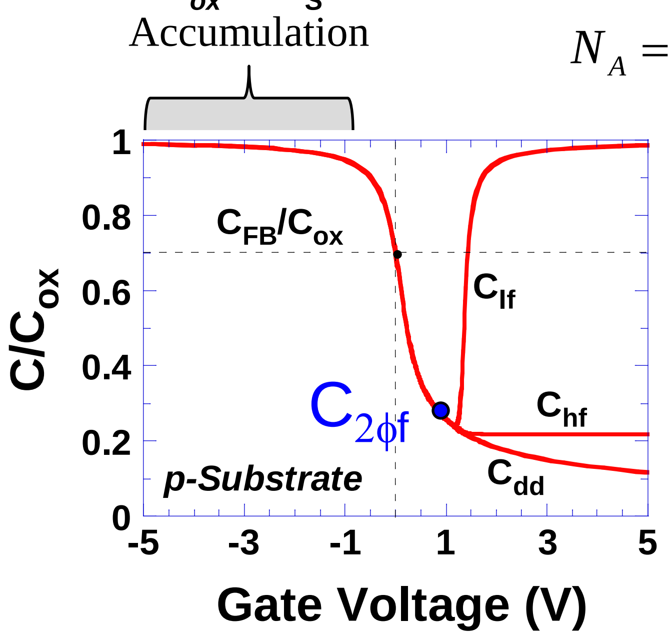
Max-Min MOS Capacitance

- ***Measure the maximum accumulation Capacitance (high frequency measurement) and the minimum capacitance in strong inversion***

$$W_{@inversion} = \sqrt{\frac{2K_S\varepsilon_O\phi_{Surface,inv}}{qN_A}}$$

$$C = \frac{C_{ox}C_S}{C_{ox}+C_S}$$

$$N_A = \frac{4\phi_F}{qK_S\varepsilon_O A^2}\frac{C_{2\phi f}^2}{\left(1-\frac{C_{2\phi f}}{C_{ox}}\right)^2} \approx \frac{4\phi_F}{qK_S\varepsilon_O A^2}\frac{C_{inversion}^2}{\left(1-\frac{C_{inversion}}{C_{ox}}\right)^2}$$

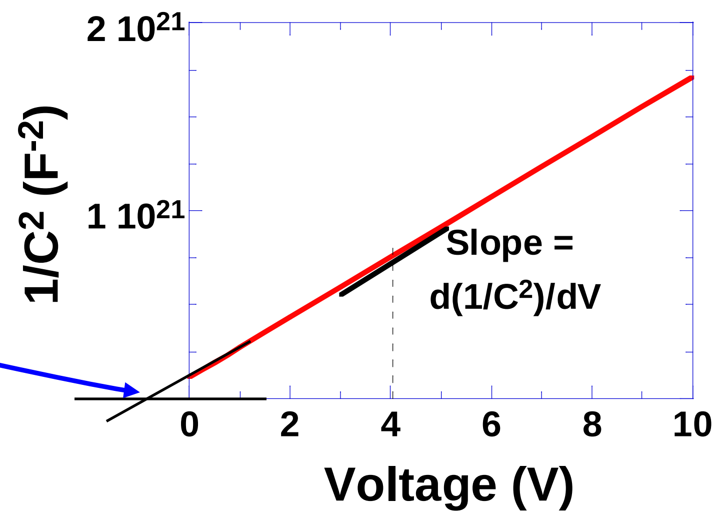


- C_{lf} = *Low frequency capacitance where the measurement frequency is small enough such that the carriers can respond to the stimulus. Sweep rate of bias is also slow.*
- C_{hf} = *High frequency capacitance where the carriers cannot respond to the stimulus. Sweep rate of bias is also slow.*
- *Cdd = When the bias sweep rate is faster than generation rate such that inversion cannot take place. Typically also measured with a high frequency stimulus.*

Built-In Voltage Determination from Capacitance-Voltage

- *The intercept of the C-V curve can determine the V_{BI}*
- **In practice, care should be exercised as in practice the ohmic-contacts (particularly the "back contact") can lead to errors in the determination of V_{BI}**
- ***Accounting for the majority carrier tail in the depletion region (introduces a kT/q factor – this effect is ignored in the depletion region approximation) The voltage intercept is,***

$$V_i = -V_{BI} + \frac{kT}{q}$$



- ***For a p-n junction,***

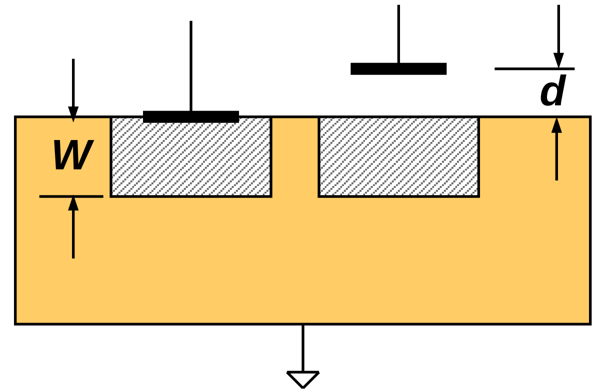
$$V_{BI} = \frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right)$$

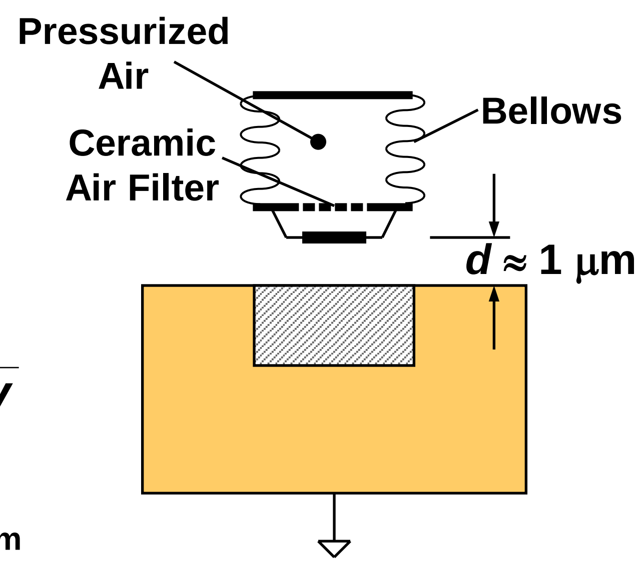
- ***For a Schottky diode,***

$$V_i = -\phi_B + \frac{kT}{q}\ln\left(\frac{N_C}{N_D}\right) + \frac{kT}{q}$$

Contactless C - V

- **Contact C-V measurements**
  - **pn junctions**
  - **Evaporated metal Schottky diodes**
  - **Mercury Schottky diodes**
  - **MOS capacitors**
- **Can also be implemented contactless**
  - **Compressed air escapes through porous disc; air cushion forms between electrode and semiconductor surface**





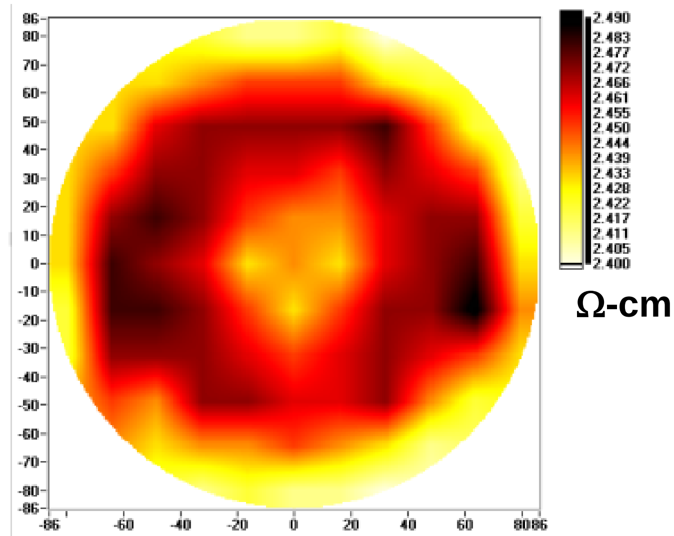
$$C = \frac{C_{air}C_S}{C_{air} + C_S};\ W = K_s\varepsilon_o A\left(\frac{1}{C} - \frac{1}{C_{air}}\right)$$

$$N_A = -\frac{C^3}{qK_s\varepsilon_o A^2 dC/dV} = \frac{2}{qK_s\varepsilon_o A^2 d(1/C^2)/dV}$$

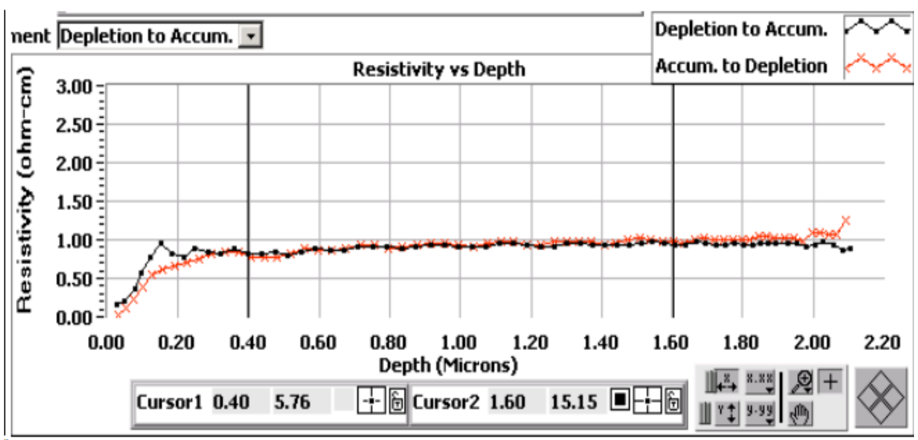
http://www.semitest.com

Contactless C -V

- Contact diameter ~ 1 mm
- Need calibrated standard wafer
- Can be used on product wafers
- Gives doping profiles
- Used mainly by wafer manufacturers



150 mm wafer



Contactless C -V

- Hg probe
- Liquid metal contacts
- Some “contact” occurs so some concern for contamination (in production) exists.
- Insulating substrates can be used (not shown)
  - Two series capacitors, one being substantially larger than the other

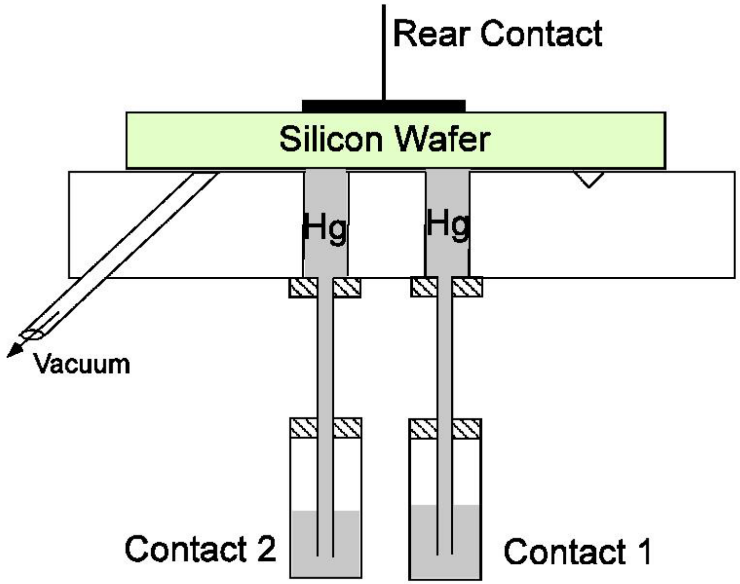
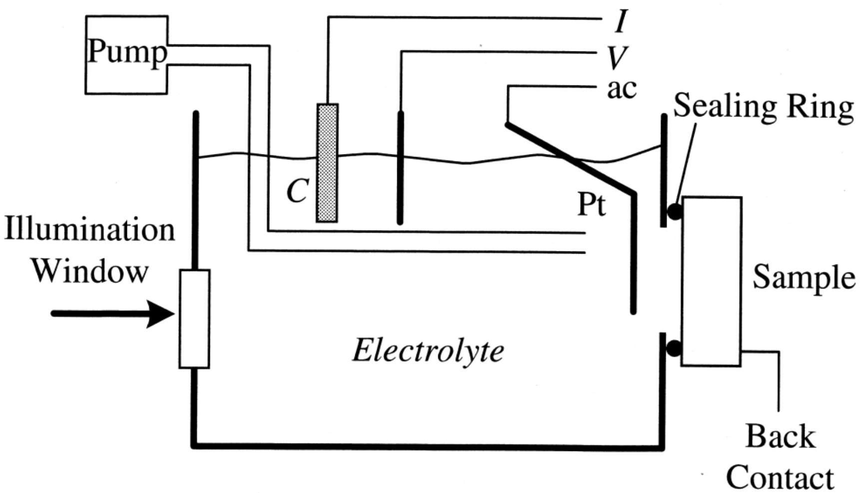


Photo from MDC Corporation

Photo from SSM Corporation

Electrochemical C -V

- Simultaneously performs CV analysis while electrochemically etching the semiconductor
- Holes needed for etching
  - P-type is easy
  - N-type needs light to generate holes
- Works best with direct bandgap semiconductors but is used with Si

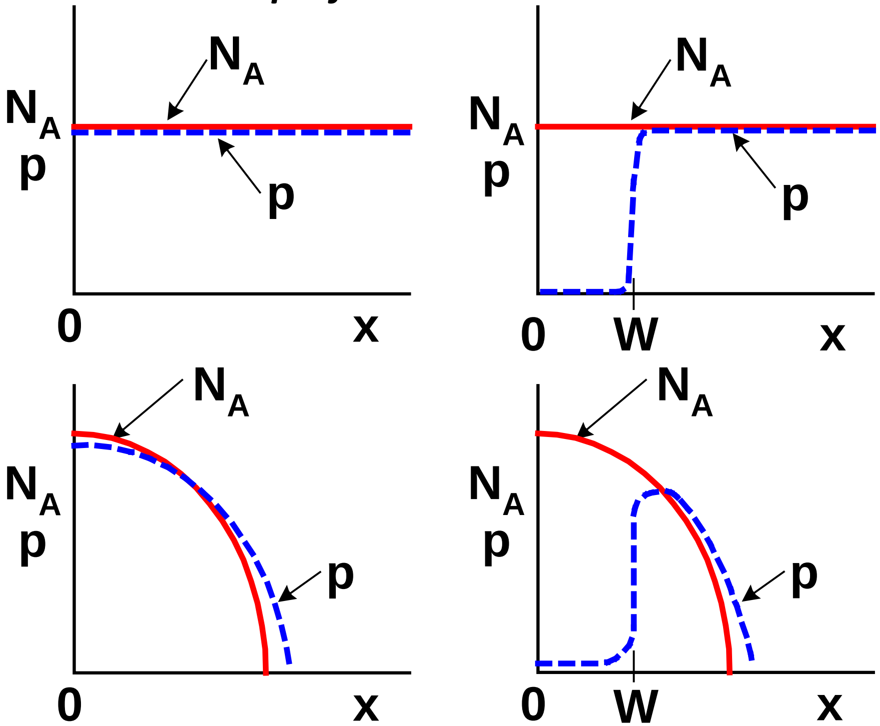


What Is Measured ?

$$L_D = \sqrt{\frac{kTK_s\varepsilon_o}{q^2(p+n)}}$$

Debye Length≡ a measure of the distance over which a charge imbalance is neutralized by majority carriers (under steady state conditions). The Debye length sets the spatial limit (resolution) of an electrically measured profile.

- **The previous equations indicate the doping profile is measured**
- **The entities that respond to the ac voltage are the majority carriers, not the dopant atoms**
- **Detailed modeling has shown that the *majority carrier* profile is measured**



Debye, Thomas-Fermi or Other Limit?

- **You will hear physicists often using the “Thomas-Fermi” length as a resolution limit instead of the Debye length – why?**
- **Both are a measure of the distance over which a charge imbalance is neutralized by majority carriers (under steady state conditions). The Debye length sets the spatial limit (resolution) of an electrically measured profile.**
  - **Debye Length valid for non-generate semiconductors at any temperature**

$$L_D = \sqrt{\frac{kTK_s\varepsilon_o}{q^2(p+n)}}$$

  - **Thomas-Fermi Screening Length is valid for degenerate semiconductors and metals and is strictly valid only at low temperatures (but is more generally applied at all temperatures)**

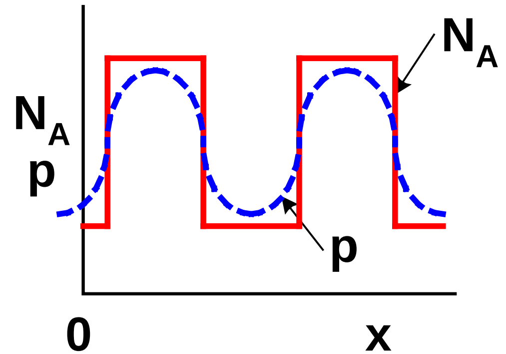
$$L_{TF} = \left(\frac{\pi}{3(p+n)}\right)^{\frac{1}{6}} \sqrt{\frac{\pi K_s\varepsilon_o\hbar^2}{q^2 m^*}}$$

  - **Quantum Confined Length: When an electron (hole) is confined by a potential well to form a 2D sheet with planar doping density N_{2D}, its spatial extent is described by a “wavefunction” that has limited width. In this special and common case, the resolution limit is described by:**

$$L_{QCS} = 2\sqrt{\frac{7}{5}}\left(\frac{4K_s\varepsilon_o\hbar^2}{9q^2m^*[N_{2D}]}\right)^{\frac{1}{3}}$$

What Is Measured ?

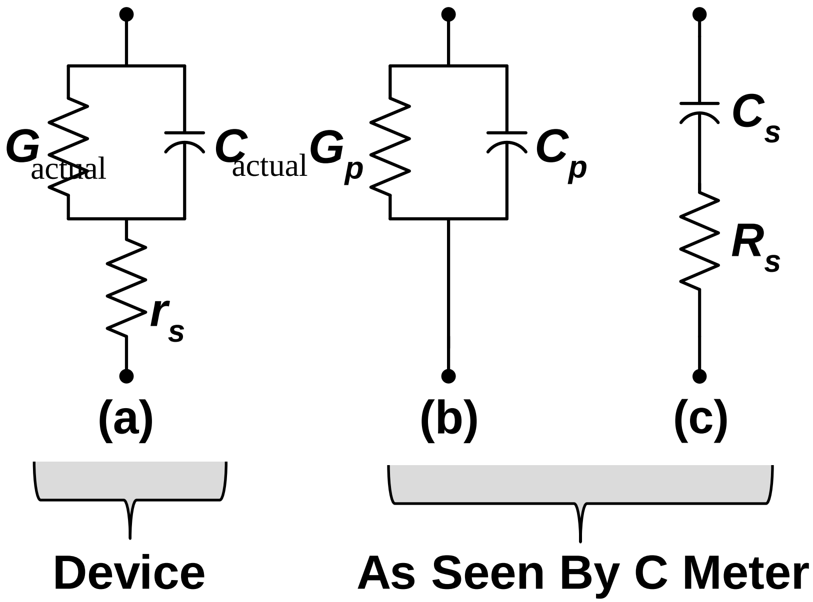
- ***C-V*** **and** V_T **profiling methods determine the carrier density, not necessarily the doping density**
- **For uniformly doped material:** $p = N_A$, $n = N_D$
- **For non-uniformly doped material:** $p \neq N_A$, $n \neq N_D$

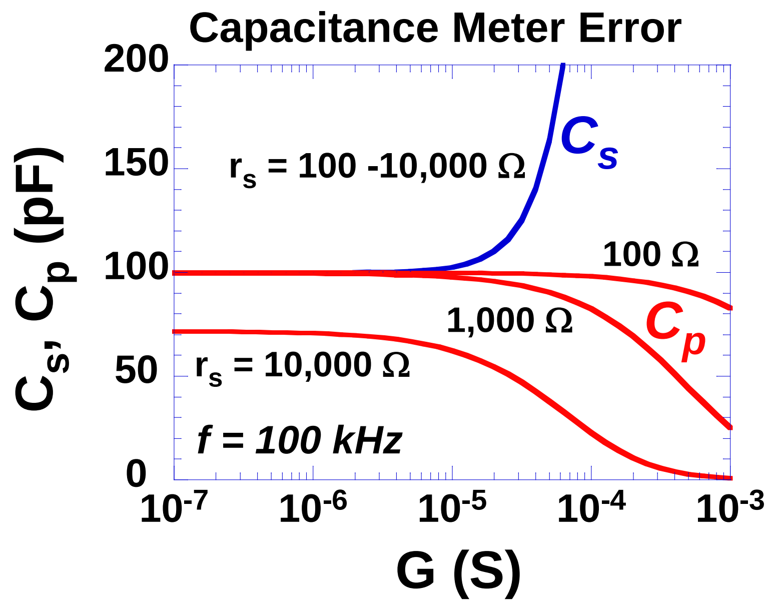


W.C. Johnson and P.T. Panousis, "The Influence of Debye Length on the C-V Measurement Doping Profiles," *IEEE Trans. Electron Dev*. ED-18, 965-973, Oct. 1973.

- **Important Limitation: When the contact area becomes comparable to the depletion width, a simple parallel plate capacitor model cannot be used. A 3D solution is needed.**

Series Resistance





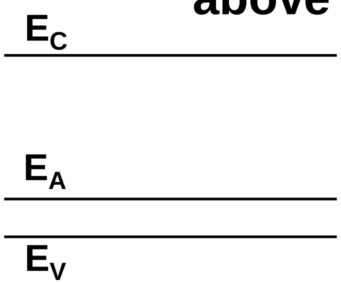
$$C_p = \frac{C_{actual}}{(1 + r_s G_{actual})^2 + (\omega r_s C_{actual})^2}; \qquad C_s = C_{actual}\left[1 + \left(\frac{G_{actual}}{\omega C_{actual}}\right)^2\right]$$

- C_p, C_s, G_p and R_s are all capacitance meter measured values.
- Series connection is preferred if series resistance is important!
- Never trust a Capacitance measurement with a quality factor ($Q=\omega C/G$) < 5.

"Deep" Concerns

- When an acceptor or defect energy is deep in the bandgap a concern as to whether the carriers can adequately respond to the ac stimulus is warranted.

- If for a p-type material with (for example) a deep acceptor at E_A eV above the valance band,



$$\tau_{emission} = \frac{e^{\left(\frac{E_A}{kT}\right)}}{\sigma_p v_{thermal} N_V} > \frac{1}{\omega_{measurement}}$$

$$\sigma_p \approx 10^{-15} cm^2 \quad v_{thermal} \approx 10^5 cm/\sec \quad N_V \approx 10^{19} cm^{-3}$$

- So for 0.16 eV deep acceptor (In in Si or Mg in GaN), $\tau_{emission}$~ 0.5 uS (~5 x [1/ω] for a 1MHz signal). $\tau_{emission}$ increases by a factor of ~10 when E_A=0.22 eV.

- In such cases, the capacitance does not accurately reflect p or N_A

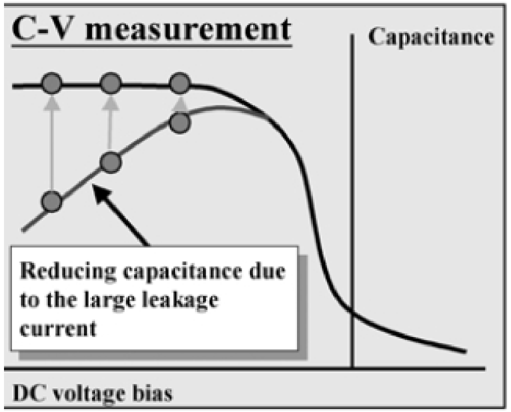
Series Resistance

- **If more than 2 parameters are needed, then more than one frequency will be required.**

$$C_{actual} = \frac{\omega_2^2 C_{S2} - \omega_1^2 C_{S1}}{\omega_2^2 - \omega_1^2}$$

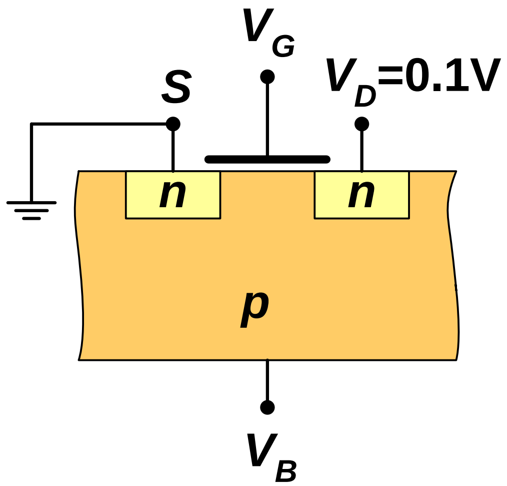
- **There are limits to the 2-frequency technique and cautions should be exercised to insure measurements are valid. The reader is encouraged to examine Agilent application note 4294-3 : "Evaluation of MOS Capacitor Oxide C-V Characteristics Using the Agilent 4294A", section 7.**

- **MAIN POINT: LEAKAGE CURRENT CAN LOWER APPARENT CAPACITANCE AND IS BIAS DEPENDENT – HUGE ERRORS!**
  - **Thin dielectrics**
  - **Semiconductors with inverted surfaces**



MOSFET Threshold Voltage

- Based on I-V not C-V so the technique scales better.
- The threshold voltage, V_T, dependence on substrate bias can be used to determine the doping profile under the gate



$$V_T = V_{FB} + 2\phi_F + \frac{\sqrt{2qK_s\varepsilon_o N_A\left(2\phi_F + V_{SB}\right)}}{C_{ox}}$$

$$V_{SB} > 0 \ for \ n-MOSFET$$

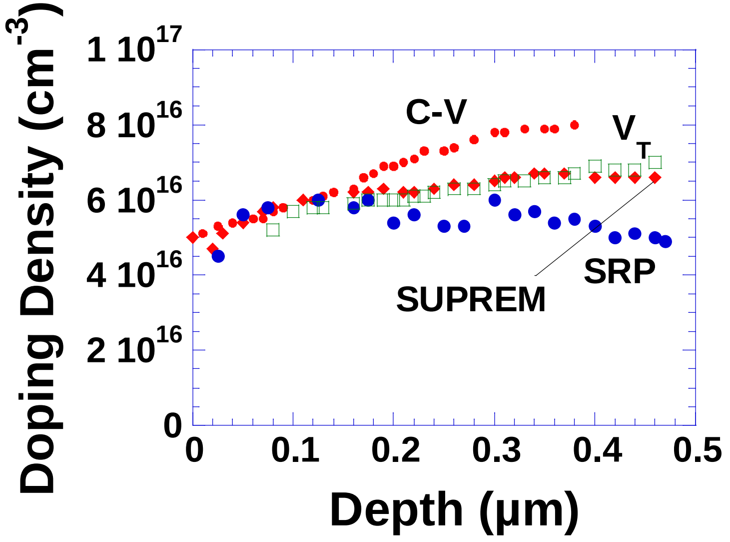
$$\frac{dV_T}{d\sqrt{2\phi_F + V_{SB}}} = \frac{\sqrt{2qK_s\varepsilon_o N_A}}{C_{ox}} = m$$

$$N_A(W) = \frac{C_{ox}^2 m^2}{2qK_s\varepsilon_o}$$

$$W = \sqrt{\frac{2K_s\varepsilon_o\left(2\phi_F + V_{SB}\right)}{qN_A}}$$

MOSFET Threshold Voltage

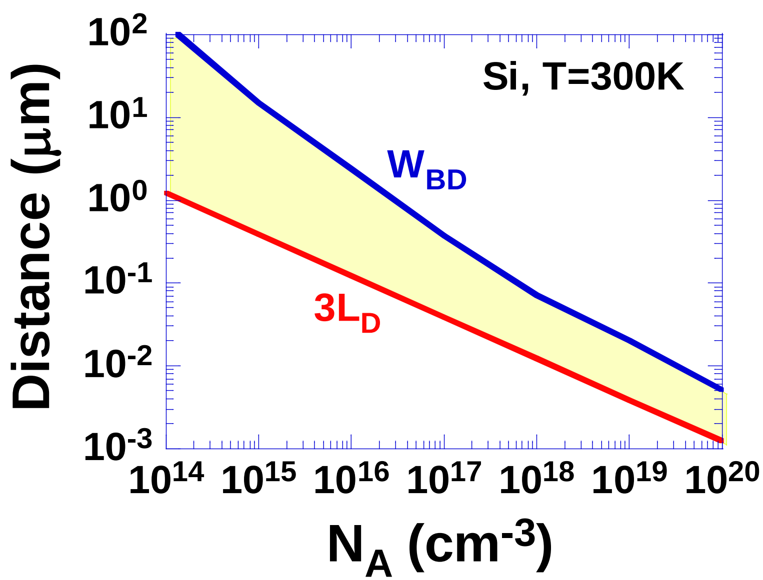
- Measure V_T as a function of back bias V_B
- Assume a value for $2\phi_F$, say 0.6 V; plot V_T vs. $(2\phi_F + V_B)^{1/2}$
- Find N_A *from the slope*,
- Use this N_A to then find a new $2\phi_F$ and replot V_T vs. $(2\phi_F + V_B)^{1/2}$
- One or two iterations are sufficient
- Find density N_A and depth *W* and plot the profile



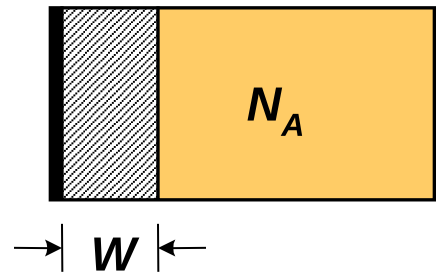
D. Feldbaumer and D.K. Schroder, "MOSFET Doping Profiling," *IEEE Trans. Electron Dev*. 38, 135-140, Jan. 1991.

Profiling Limits

- There are two limits
  - Close to surface
  - Junction breakdown

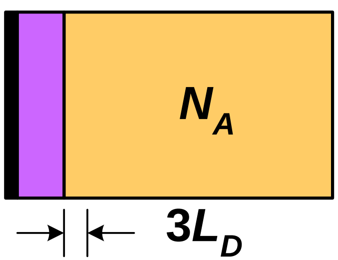


Schottky:



$$W = \sqrt{\frac{2K_s\varepsilon_o V_{bi}}{qN_A}} \approx 5-6L_D$$

MOS-C:



$$L_D = \sqrt{\frac{kTK_s\varepsilon_o}{q^2 N_A}} = \frac{410}{\sqrt{N_A}}\ cm$$

$$for\ Si\ at\ T = 300\,K$$

Review Questions

- What is *secondary ion mass spectrometry*?
- Name a disadvantage of *spreading resistance* profiling.
- How is the *capacitance* measured?
- Why is $1/C^2$ - V preferred over $C – V$?
- What is important in contactless $C – V$?
- What is measured in most profiling techniques, *i.e*., doping density or majority carrier density?
- What is the *Debye length*?
- What does series resistance do?
- How does the threshold voltage technique work?
- What determines the profiling limits?