## Lecture 2

- Introduction to semiconductors
- Structures and characteristics in semiconductors
  - Semiconductor p-n junction
  - Metal Oxide Silicon structure
  - Semiconductor contact

## Literature

- Glen F. Knoll, Radiation Detection and Measurements, chapters 11,13,19
- Semiconductor Radiation Detectors, Gerhard Lutz, Springer-Verlag, 1999
- Nanohub tutorials

# Elements used in semiconductor sensors

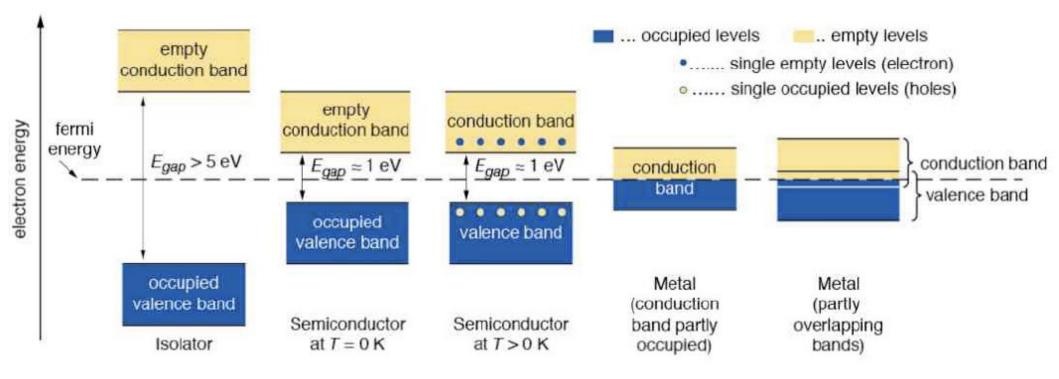


Compound semiconductor

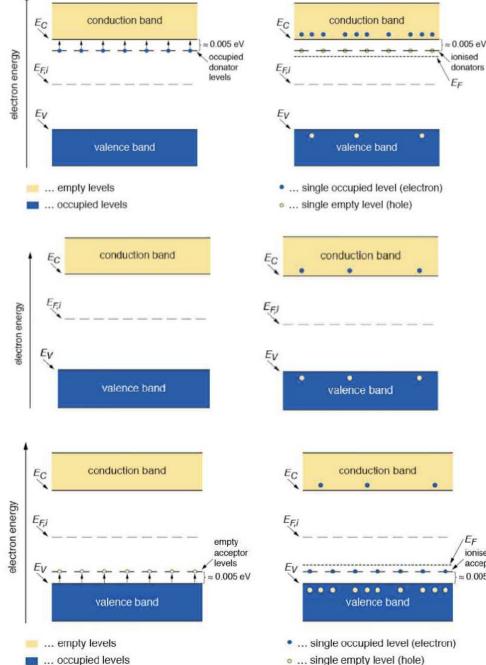
1																	18
IA																	VIIIA
1 H																	2 He
Hydrogen	2											13	14	15	16	17	Helium
1.00794	IIA											IIIA	IVA		VIA	VIIA	4.002602
3 Li	4 Be		-									5 B	6 C	7 N	8 0	9 F	10 Ne
Löthöum	Bery llium		PER.	IODIC	TABI	EOF	THEE	LEMI	INTS			Borm		Nitrogen	Oxygen	Fluorine	Necn
6.941	9.012182											10.811	12.0107	14.00674	15.9994	18.9984032	20.1797
11 Na	12 Mg											13 A	14 Si	15 P	16 S	17 O	18 Ar
Sodium	Magnesi um	3	4	5	6	7	8	9	10	11	12	Ahminun	Silicon	Phosph.	Sulfar	Chlorine	Argon
22.989770	24.3050	IIIB	IVB	VB	VIB	VIIB	_	VIII		IB	HB	26.981538	28.0855	30.973761	32.066	35.4527	39.948
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	3 As	34 Se	35 Br	36 Kr
Potassium	Calcium	Scandium	Titanium	Vanadium	Chromium	Manganese	Iron	Cobalt	Nickel	Copper	Zime	Gallium	German.	Arsenic	Selenium	Bromine	Krypton
39.0983	40.078	44.955910	47.867	50.9415	51.9961	54.938049	55.845	58.933200	58.6934	63.546	65.39	69.723	72.61	74.92160	78.96	79.904	83.80
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sh	51 Sb	52 Te	53 I	54 Xe
Ru bidi um	Strontium	Yttrium	Zirconium	Niobium	Molybd.	Technet.	Ruthen.	Rhodium	Palladium	Silver	Cadminm	In dimm	Tin	Antimony	Tellurium	Iodine	Xenon
85.4678	87.62	88.90585	91.224	92.90638	95.94	(97.907215)	101.07	102.90550	106.42	107.8682	112.411	114.818	118.710	121.760	127.60	126.90447	131.29
55 Cs	56 Ba	57-71	72 Hf	73 Ta	74 W	75 Re	76 Os	77 k	78 Pt	79 Au	80 Hg	81 TI	82 Pb	83 Bi	84 Po	85 At	86 Rn
Cesinm	Barium	Lantha-		Tantalum	Tungsten	Rhenium	Osminm	Iridium	Platimum	Gold	Mercury	Thallium	Lead	Bismuth	Polonium	Astatine	Radon
132.90545	137.327	nides	178.49	180.9479	183.84	186.207	190.23	192.217	195.078	196.96655	200.59	204.3833	207.2	208.98038	(208.982415)	(209.987131)	(222.017570)
87 Fr	88 Ra	89-103	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110	111	112						
Francium	Radium	Actinides	Rutherford.	Dubnium	Seaborg.	Bohrium	Hassium	Meitner.									
(223.019731)	(226.025402)		(261.1089)	(262.1144)	(263.1186)	(262.1231)	(265.1306)	(266.1378)	(269, 273)	(272)	(277)						

Lanthanide	57	La	58	Ce	59	Pr	60	Nd	61	Pm	62	Sm	63	Eu	64	Gd	65	Тb	66	Dy	67	Ho	68	Er	69	Tm	70	Yb	71	Lu
series	Lanti				Praseo																									
	138.9	055	140.	116	140.90	765	144	.24	(144.9	12745)	150	.36	151	964	157	25	158.9	2534	162	.50	164.9	8032	167	.26	168.9	3421	173	.04	174.9	967
Actinide	89	Ac	90	Th	91	P <sub>2</sub>	92		93	No	9.4	p <sub>m</sub>	<u>05</u>	Am	96	Cm	97	Rk	98	Cf	99	Fe	100	Em	101	Md	102	No	103	Lr.
series					Protac																									mc.
	(2 27.02	7747	232.0	381	231.03	588	238.0	289	(237.0	48166)	(244.05	4197)	(243.0	61372)	(247.07	0346)	(247.0	70298)	(251.0	19579)	(252.)	38297)	(257.0	95096)	(258.0	98427)	(259.1	1011)	(262.1	(98

## Basics on semiconductors



## Semiconductor types



n-type

- ✓ Negative donor ions-> excess of electrons in conduction band
- Doping with elements from VA, VIA

Intrinsic

- Equal amount of electrons in ~ conduction band and holes in valence band
- Pure silicon. ~

p-type

Ef

ionised

acceptors

≈ 0.005 eV

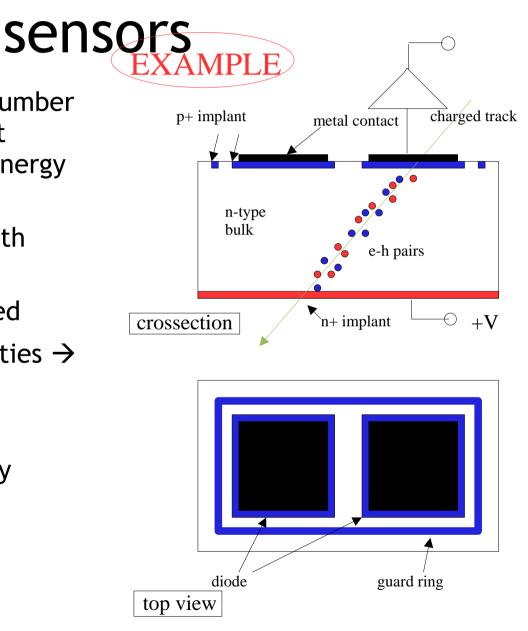
- ✓ Positive acceptor ions-> excess of holes in valence band
- Doping with elements from IIA, IIIA

## Properties of common semiconductors

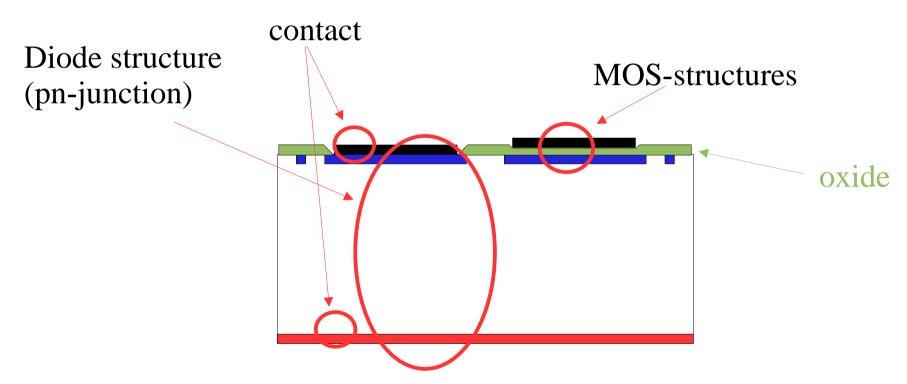
Substance	Si	Ge	GaAs	С	CdTe
Optical transition	Indirect	Indirect	Direct	Indirect	Direct
Energy gap [eV]	1.12	0.67	1.52	5.48	1.56
Intrinsic carrier					
concentration [cm <sup>-3</sup> ],					
n,	1,5 x 10 <sup>10</sup>	2,4 x 10 <sup>12</sup>	2,1 x 10 <sup>10</sup>		
Mean energy for					
electron-hole pair					
creation [eV]	3.63	2.96	4.35	13.1	3.9
Drift mobility for					
electrons, μ <sub>e</sub> [cm²/Vs}	1350	3900	8800	1800	10500
Drift mobility for					
holes, µ <sub>h</sub> [cm²/Vs}	480	1900	320	1200	100
Intrinsic resistivity [ $\Omega$					
cm}	2,30 x 10 <sup>5</sup>	47			

## Properties of semiconductor

- ✓ Small band gap → large number of charge carriers per unit energy loss → excellent energy resolution
- High density compared with gaseous detectors
- ✓ High mobility → high speed
- ✓ Excellent material properties → rigidity, thermal
- Flexible to design
- Linearity and gain stability
- Tolerant to radiation
- High spatial resolution

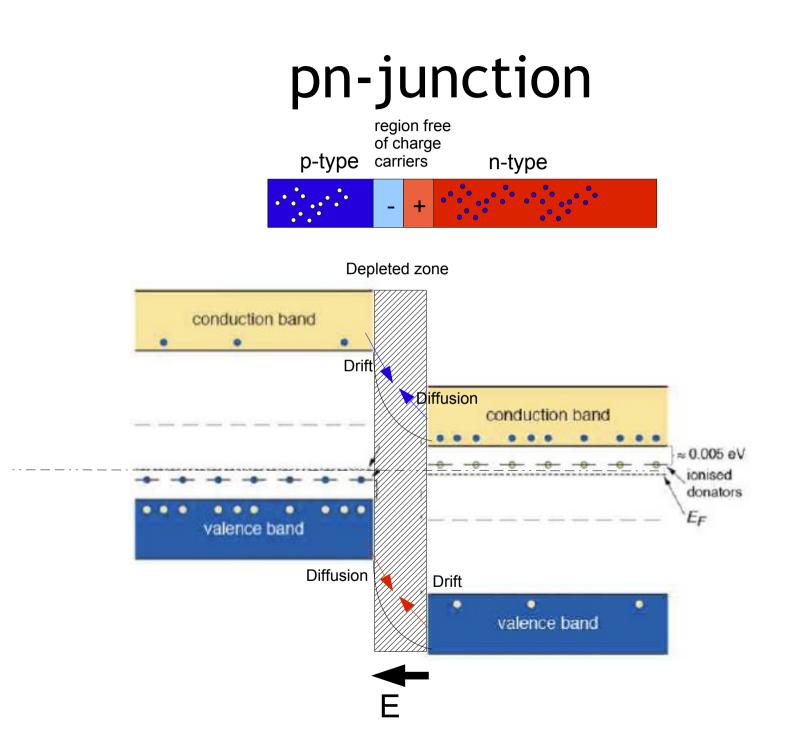


# Structures in semiconductor sensors

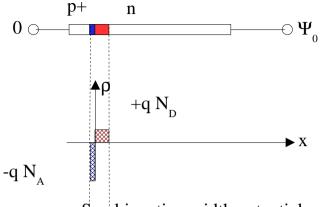


Most important and commonly used structures in semiconductor sensors are

- Diode structure, pn-junction and np-junction
- MOS structure (Metal-Oxide-Semiconductor)
- Contact (OHMIC,SCHOTTKY)



## Diode structure (1 dimension)



Smal junction width, potential

 $\Psi_0 = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$  $V_T = \frac{k_B T}{q} \approx 26 \, mV$ 

Study a typical n-bulk sensor structure:

Doping concentration in n-region (bulk) is low while the p-region has been implanted with high doping concentration. (Asymmetric junction)

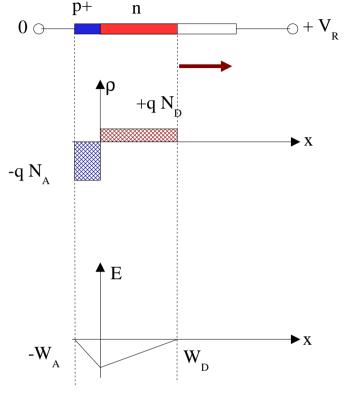
 $N_A >> N_D$ 

The built in potential  $(\Psi_o)$  in the junction is created by thermal diffusions of electrons into p-region and holes into n-region.

 $N_A, N_D$  = concentration of acceptor and donor ions.

 $n_i$  = concentration of charge carriers in the bulk (1.5E10 cm<sup>-3</sup> for Silicon at 300K)

## Diode structure (cont. 1)



$$E = -\frac{dV}{dx} = -\frac{qN_A}{\epsilon_R\epsilon_0}(x+W_A)$$

If an external reverse bias voltage  $V_{R}$  is applied the junction will grow. The charge balance in the structure is maintained which results in:

 $W_A N_A = W_D N_D$ 

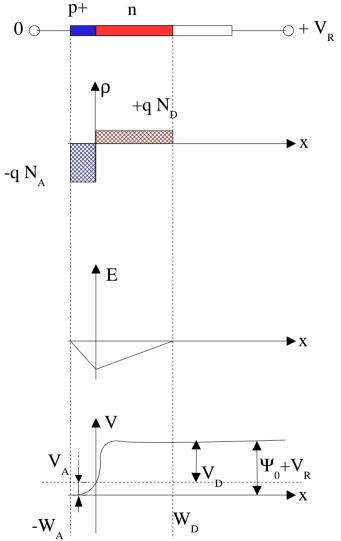
For the region -W<sub>A</sub> to x=0 the potential across the region is described by the Poisson equation

$$\frac{d^2 V}{d x^2} = -\frac{\rho}{\epsilon_R \epsilon_0} = \frac{q N_A}{\epsilon_R \epsilon_0}$$

Integration over the p+ region and setting boundary condition  $E(-W_A)=0$  results in the field in that region

Integration once more gives the potential in the region =>

## Diode structure (cont. 2)



The potential in the region with boundary condition  $V(-W_{A}) = 0$ 

becomes

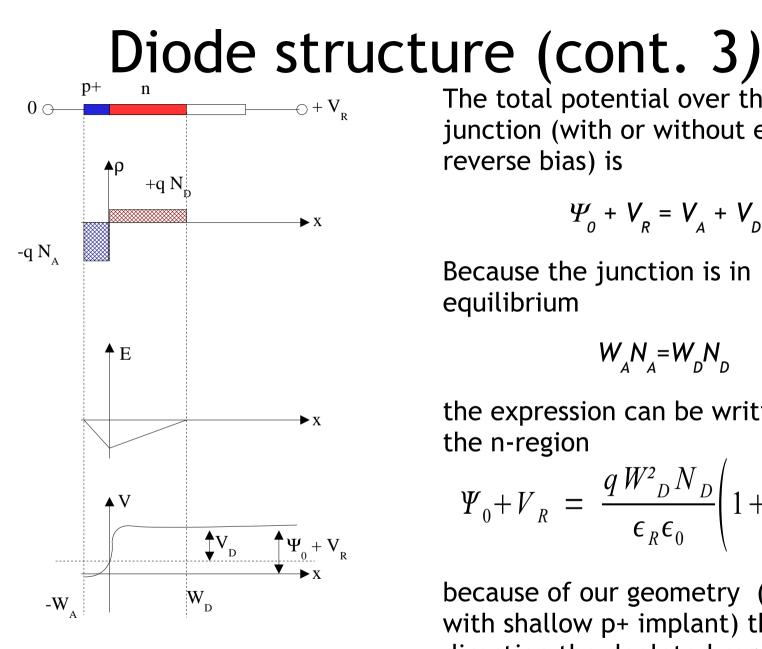
$$V = \frac{q N_A}{\epsilon_R \epsilon_0} \left( \frac{x^2}{2} + W_A x + \frac{W_A^2}{2} \right)$$

 $-W_{A} < x < 0$ 

Use this expression to define the potentials  $V_{A}$  at x=0

$$V_A = \frac{q N_A}{\epsilon_R \epsilon_0} \frac{W_A^2}{2}$$

We can with similar considerations determine  $V_{D}$  at x=0  $V_{D} = \frac{q N_{D}}{\epsilon_{R} \epsilon_{0}} \frac{W_{D}^{2}}{2}$ 



The total potential over the junction (with or without extra reverse bias) is

$$\Psi_0 + V_R = V_A + V_D$$

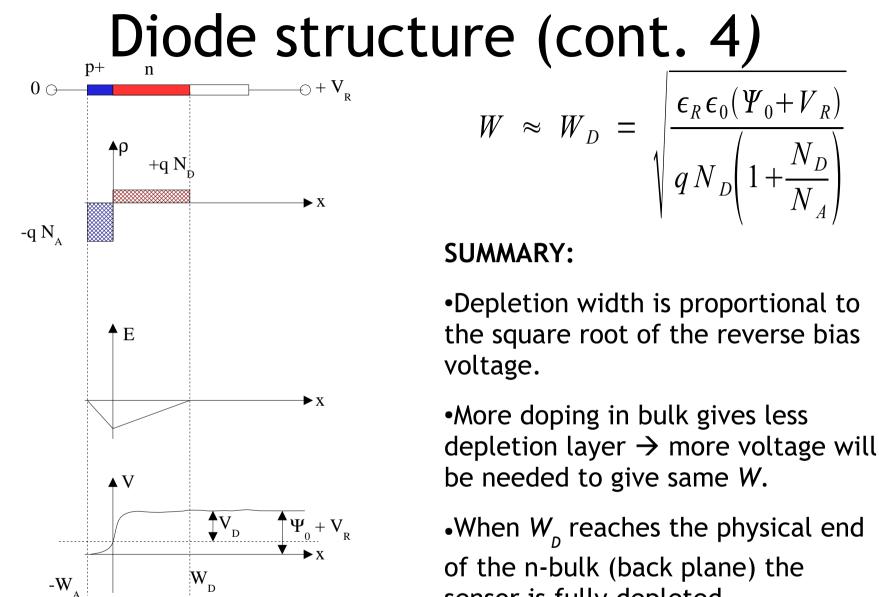
Because the junction is in equilibrium

$$W_A N_A = W_D N_D$$

the expression can be written for the n-region

$$\Psi_0 + V_R = \frac{q W_D^2 N_D}{\epsilon_R \epsilon_0} \left( 1 + \frac{N_D}{N_A} \right)$$

because of our geometry (n-bulk with shallow p+ implant) the only direction the depleted region can grow is in the n- region  $\rightarrow$  $W_{D} >> W_{A} = W$ 



sensor is fully depleted.

## Important features

- Macroscopic features of a good semiconductor sensor are
  - ✓ Low capacitive load  $\rightarrow$  low noise in readout electronics
  - ✓ Low leakage current → low noise in readout electronics
  - Good charge collection
  - ✓ High speed

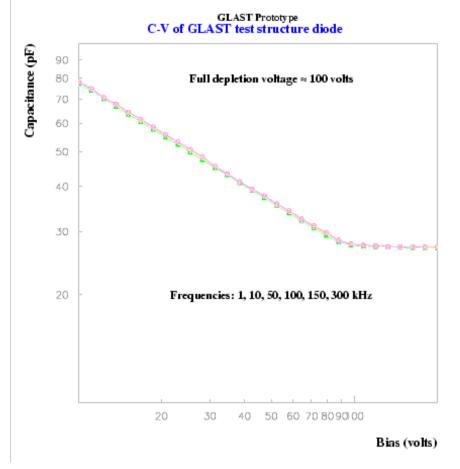
## Characteristics of the diode Capacitance (C-V) Structure

The capacitance of the diode influences the noise of the readout electronics by loading the amplifier (will be discussed later in this series). The capacitance of the pnjunction is given by

$$C_{j} = \frac{\epsilon_{R}\epsilon_{0}}{W_{D}}$$

The capacitance of the junction will decrease when reverse bias voltage is applied until full depletion is reached.

#### WE WANT LOW CAPACITANCE!



# Characteristics of the diode Leakage current (I-V)

✓ diffusion current

Electrons generated in the p+ region and holes generated in the n+ region diffuse to the junction and are collected by electrodes. Small effect for Si but large for Ge at room temperature.

$$J_s = q \sqrt{\frac{D_P}{\tau_P}} \frac{n_i^2}{N_D}$$

where  $D_p$  is the diffusion constant for electrons in the p+ region and  $\tau_p$ is the lifetime of the electron generating current

This is the dominated current in a good sensor. The current is due to generation-recombination in the depleted region.

 $J_g = q g W$ 

g is the generation rate dependent of the intrinsic carrier concentration,  $n_i$ .

$$g = \frac{n_i}{\tau_g}$$

 $\tau_{_g}$  is the generation lifetime (~10^{-3} s)

# Characteristics of the diode structure

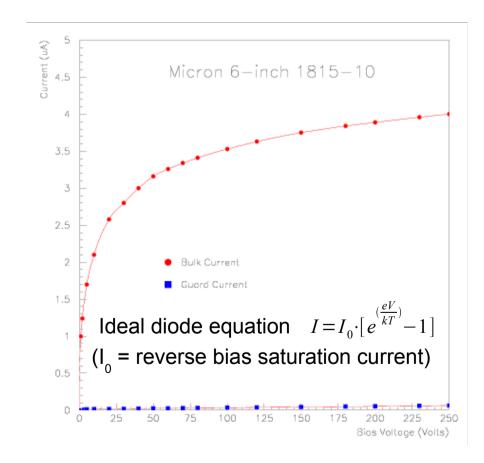
#### • Leakage current (I-V)

✓ generating current(cont.)

The current is also sensitive to temperature. 8K increase in temperature doubles the current!!

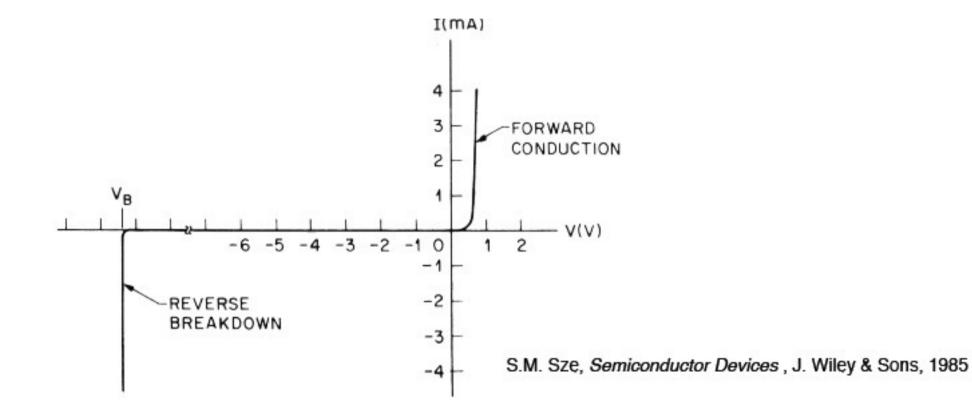
✓ surface current

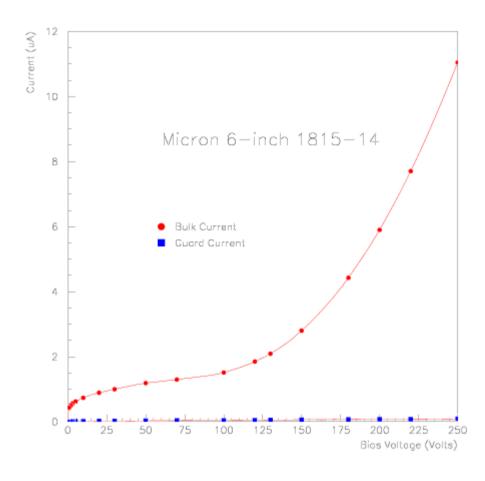
Surface current is a contribution on complex effects happening in the boarder between the semiconductor and surface oxide. The current level is very dependent on processing quality and handling.



GOOD I-V curve

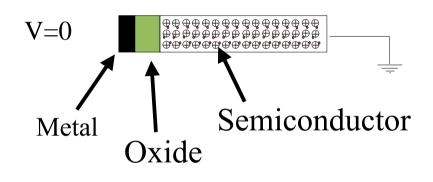
## More on IV-characteristics





#### BAD I-V curve !

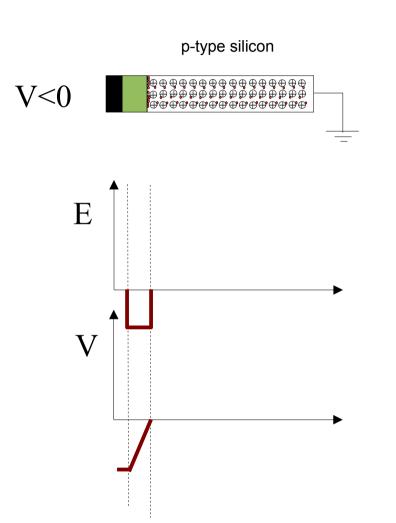
## Metal-Oxide-Semiconductor structure



 MOS structure (or more general Metal-Insulator-Semiconductor, MIS) is widely used in electronics industry to make gates and in sensor industry to make ACcoupled sensors

- The figure shows a 1dimensional picture of a MOS structure with a n-doped semiconductor insulated from a metal layer with a oxide.
- If the potential at the metal is at the same potential as the semiconductor and the charge carrier electrons in the n-type semiconductor will be homogeneously distributed → no field across the oxide. This is called the <u>Flat Band condition</u>.

## MOS in accumulation

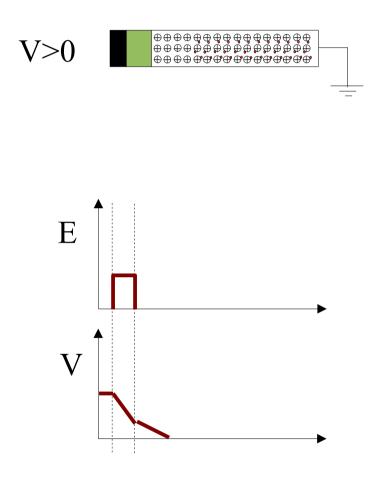


- If the potential on the metal is set below the voltage of the semiconductor the holes are attracted to the semiconductoroxide interface where they accumulate to a very thin layer. This is called <u>Accumulation</u> <u>condition.</u>
- A field is created across the oxide.

$$E_{ox} = \frac{Q_{acc}}{\epsilon_{ox}\epsilon_0}$$

$$V = E_{ox}d_{ox} = -\frac{Q_{acc}}{C_{ox}}$$

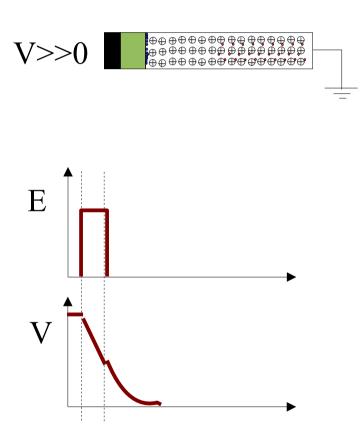
## MOS in depletion



- If the potential on the metal is increased slightly above the voltage of the semiconductor the holes are repelled from the semiconductor-oxide interface and a negative space charge region is formed. This is called <u>Depletion condition</u> (used by CCD detectors)
- A field is created across the oxide and the space charge regions.

$$E_{ox} = -\frac{q N_D}{\epsilon_{ox} \epsilon_0} d_s$$
$$E_s = -\frac{q N_D}{\epsilon_s \epsilon_0} d_s$$

## MOS in inversion



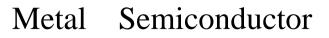
 If the potential on the metal is very much above the voltage of the semiconductor the holes are pushed even further away from the semiconductor-oxide interface. Thermally generated electron-holes pairs are separated from each other thus an inversion layer of electrons is built up at the interface. This is called <u>Inversion condition.</u>

$$E_{ox} = -\frac{q N_D}{\epsilon_{ox} \epsilon_0} d_{max} - \frac{Q_{inv}}{\epsilon_{ox} \epsilon_0}$$

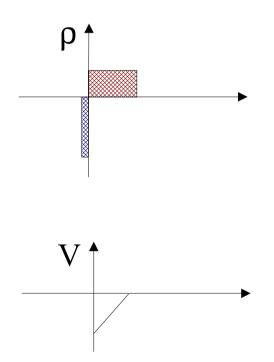
$$E_{s} = -\frac{q N_{D}}{\epsilon_{s} \epsilon_{0}} d_{s}$$

## Schottky contact

- A contact to the semiconductor can be made by deposition of a metal layer directly onto the silicon. This metalsemiconductor contact was one of the first practical semiconductor showing rectifying properties, the <u>Schotky contact</u> (used in surface barrier detectors).
- If the doping concentration under the metal is high the characteristic resistance of the junctions becomes small, the rectifying feature turns into an <u>Ohmic contact.</u>







#### END LECTURE