Resistors: Heaters and Temperature Sensors

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12-5-11 resistor_mems.ppt

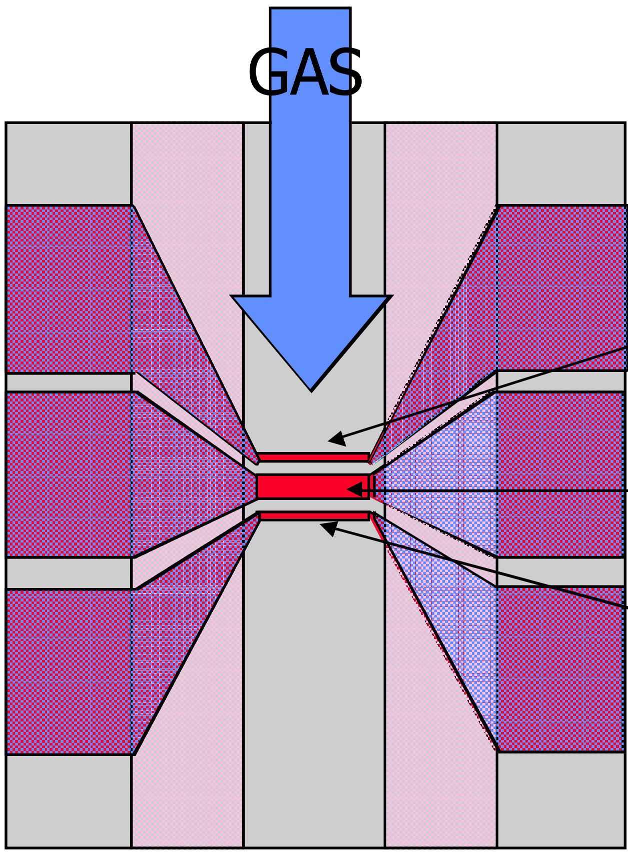
OUTLINE

Introduction
Resistors
Resistive Temperature Sensors
Heaters

INTRODUCTION

Heaters are used in many MEMS applications including ink jet print heads, actuators, bio-mems, chemical detectors and gas flow sensors. Resistors are used in temperature sensors, pressure sensors, accelerometers and light sensors. This module will discuss the resistor as a heater and as a sensor.

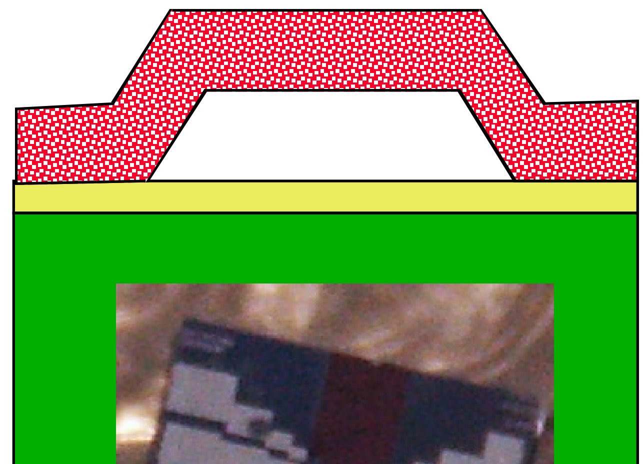
SURFACE MICROMACHINED GAS FLOW SENSOR

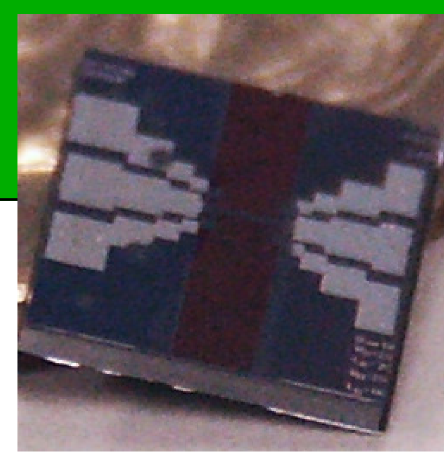


Upstream Polysilicon Resistor

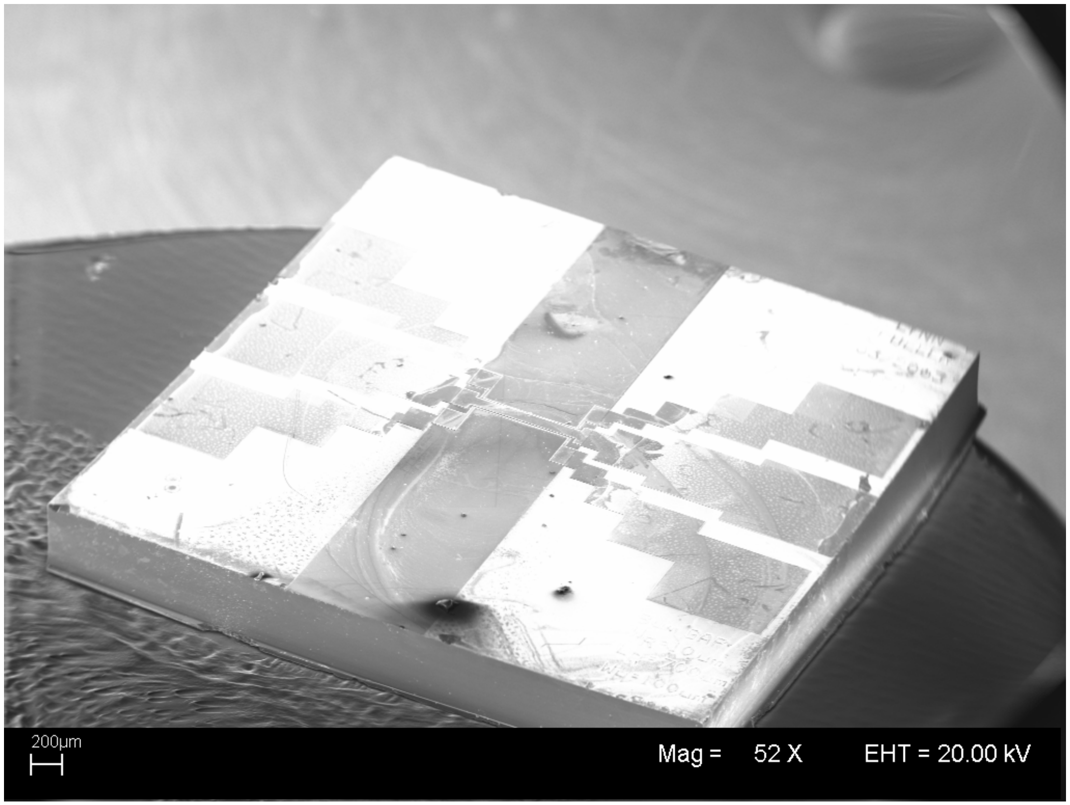
Polysilicon heater

Downstream Polysilicon Resistor





SURFACE MICROMACHINED GAS FLOW SENSOR



L of heater & resistor = 1mm

W (heater) = 50um

W (resistors) = 20um

Gap = 10um

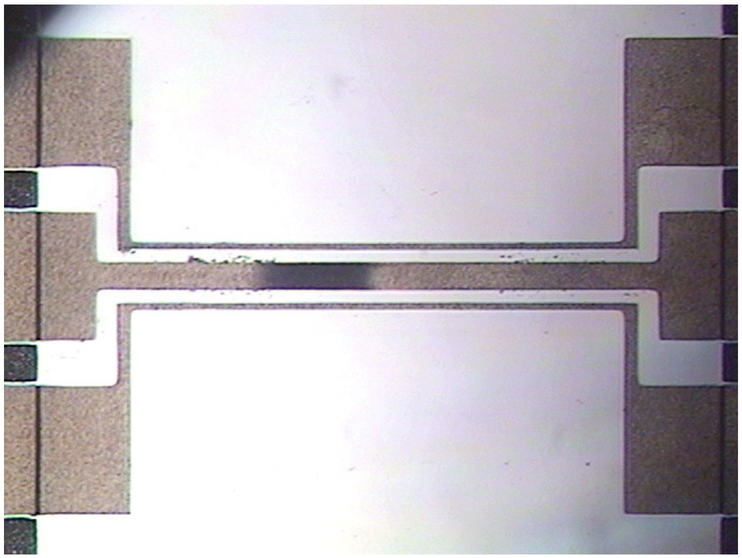
V applied = 27V to 30.5V

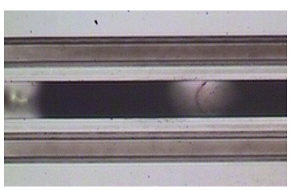
Temp ~600 °C at 26 volts

Lifetime > 10 min at 27 volts (possibly longer, did not test)

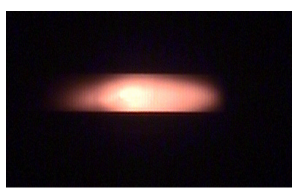
Vee Chee Hwang, 2004

THERMIONIC GAS DETECTOR

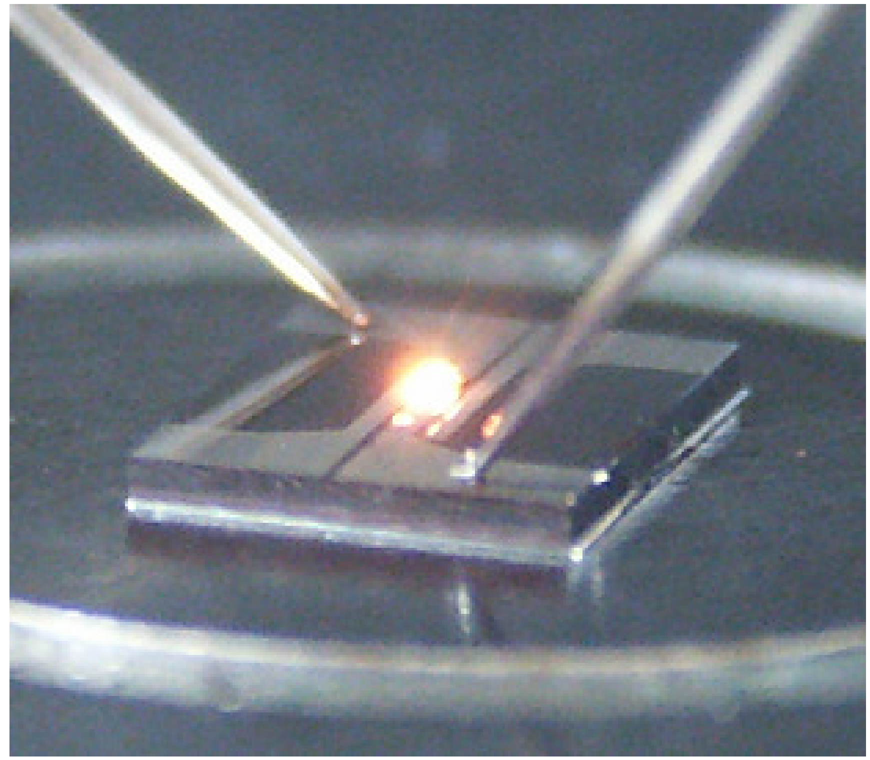




Cold

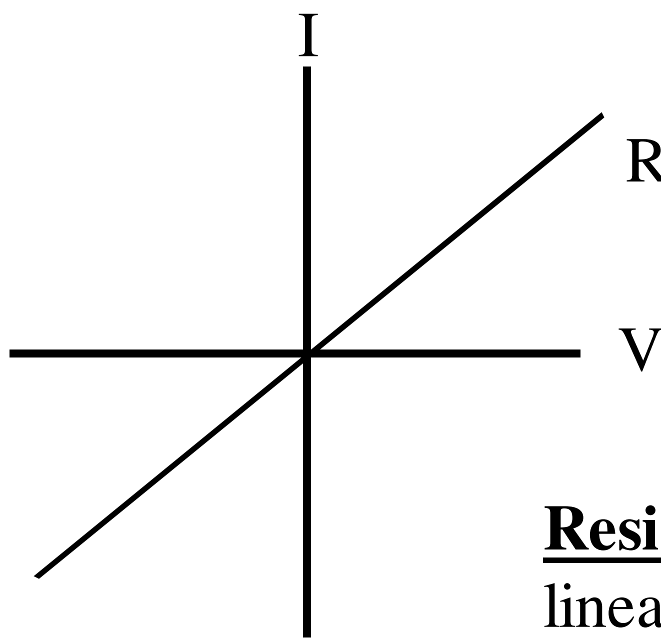


Hot

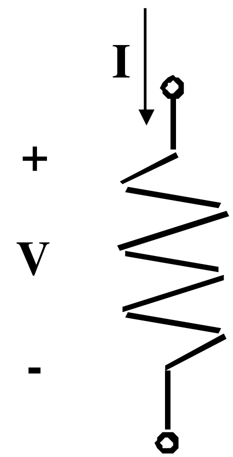


Robert Manley, 2004

OHM'S LAW



R = V/I = 1/slope



<u>Resistor</u> a two terminal device that exhibits a linear I-V characteristic that goes through the origin. The inverse slope is the value of the resistance.

THE SEMICONDUCTOR RESISTOR

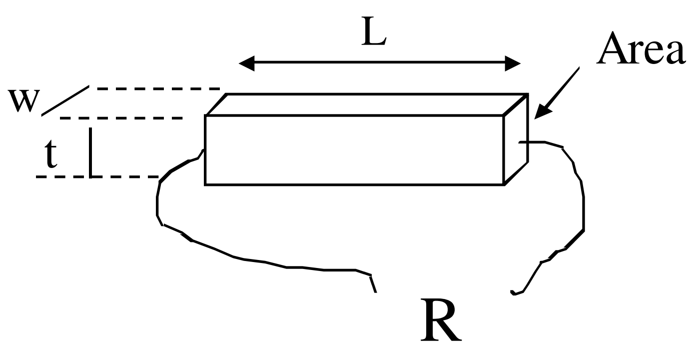
Resistance = R = ρ L/Area = ρ_s L/w ohms

Resistivity = Rho = ρ = $1/(q\mu_n n + q\mu_p p)$ ohm-cm

Sheet Resistance = Rhos = ρ_s = $1/(\int q\,\mu(N)\,N(x)\,dx) \sim 1/(q\mu\ \text{Dose})$ ohms/square

$\rho_s = \rho / t$

Rho is the bulk resistivity of the material (ohm-cm)
Rhos is the sheet resistance (ohm/sq) = Rho / t



Note: sheet resistance is convenient to use when the resistors are made of thin sheet of material, like in integrated circuits.

R = Rho L / Area
= Rhos L/W

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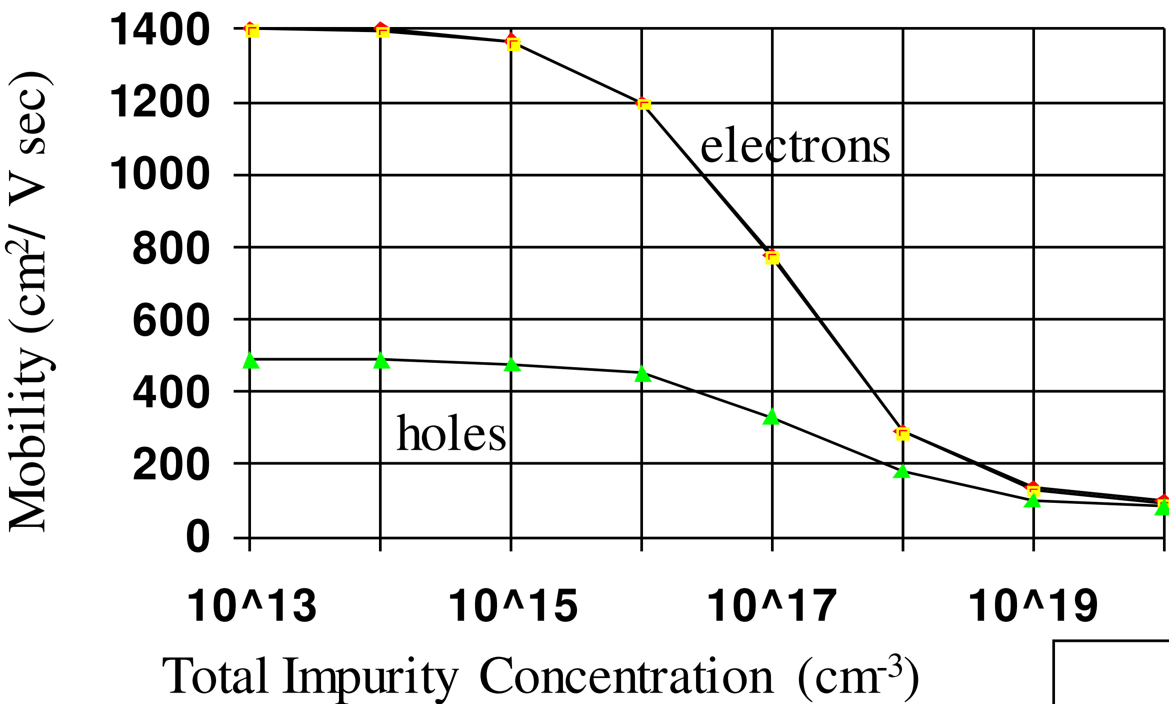
MOBILITY



Electron and hole mobilities in silicon at 300 K as functions of the total dopant concentration (N). The values plotted are the results of the curve fitting measurements from several sources. The mobility curves can be generated using the equation below with the parameters shown:

$$\mu(N) = \mu_{mi} + \frac{(\mu_{max} - \mu_{min})}{\{1 + (N/N_{ref})^{\alpha}\}}$$

Parameter	Arsenic	Phosphorous	Boron
μ_{min}	52.2	68.5	44.9
μ_{max}	1417	1414	470.5
N_{ref}	9.68X10^16	9.20X10^16	2.23X10^17
α	0.680	0.711	0.719

From Muller and Kamins, 3rd Ed., pg 33

TEMPERATURE EFFECTS ON MOBILITY

Derived empirically for silicon for T in K between 250 and 500 °K and for N (total dopant concentration) up to 1 E20 cm-3

$$\mu n\ (T,N) = 88\ Tn^{-0.57} + \frac{1250\ Tn^{-2.33}}{1 + [\ N / (1.26E17\ Tn^{\ 2.4})]\ \hat{}0.88\ Tn^{\ -0.146}}$$

$$\mu p\ (T,N) = 54.3\ Tn^{-0.57} + \frac{407\ Tn^{-2.33}}{1 + [\ N / (2.35E17\ Tn^{\ 2.4})]\hat{}\ 0.88\ Tn^{\ -0.146}}$$

Where Tn = T/300

From Muller and Kamins, 3rd Ed., pg 33

MOBILITY CALCULATIONS

MICROELECTRONIC ENGINEERING 3/13/2005

CALCULATION OF MOBILITY Dr. Lynn Fuller

To use this spreadsheed change the values in the white boxes. The rest of the sheet is protected and should not be changed unless you are sure of the consequences. The calculated results are shown in the purple boxes.

CONSTANTS	VARIABLES			CHOICES	
Tn = T/300 1.13					1=yes, 0=no
	Temp=	338	°K	n-type	1
	N total	1.00E+18	cm-3	p-type	0
				<100>	

Kamins, Muller and Chan; 3rd Ed., 2003, pg 33

mobility= 196 cm2/(V-sec)

TEMPERATURE COEFFICIENT OF RESISTANCE

$\Delta R/\Delta T$ for semiconductor resistors

R = Rhos L/W = Rho/t L/W

assume W, L, t do not change with T

Rho = 1/(qµn + qµp) **where µ is the mobility which is a function of temperature, n and p are the carrier concentrations which can be a function of temperature (in lightly doped semiconductors)**

as T increases, µ decreases, n or p may increase and the result is that R usually increases unless the decrease in µ is cancelled by the increase in n or p

RESISTANCE AS A FUNCTION OF TEMPERATURE

$$R(T,N) = \frac{1}{q\mu_n(T,N)\ n + q\ \mu_p\ (T,N)\ p} \ \frac{L}{Wt}$$

L, W, t, are physical length width and thickness and do not change with T
Constant q = 1.6E-19 coul
μ_n (T,N) = see expression on previous page
μ_p (T,N) = see expression on previous page
n = Nd and p = 0 if doped n-type
n=0 and p = Na if doped p-type
n = p = ni(T) if undoped, see exact calculation on next page

$$ni(T) = A\ T^{3/2}\ e^{-(Eg)/2KT} = 1.45E10 \ @ \ 300\ °K$$

EXACT CALCULATION OF n AND p

CONSTANTS			VARIABLES			
K	1.38E-23	J/K				
q	1.60E-19	Coul				
Ego	1.16	eV				
a	7.02E-04					
B	1.11E+03					
h	6.63E-34	Jsec	Nd =	3.00E+16	cm-3	Donor Concentration
εo	8.85E-14	F/cm	Ed=	0.049	eV below Ec	
εr	11.7		Na =	8.00E+15	cm-3	Acceptor Concentration
ni	1.45E+10	cm-3	Ea=	0.045	eV above Ev	
Nc/T^3/2	5.43E+15					
Nv/T^3/2	2.02E+15		Temp=	300	°K	

Donor and Acceptor Levels (eV above or below Ev or Ec)

Boron	0.044
Phosphorous	0.045
Arsenic	0.049

CALCULATIONS: (this program makes a guess at the value of the fermi level and trys to minimize the charge balance)

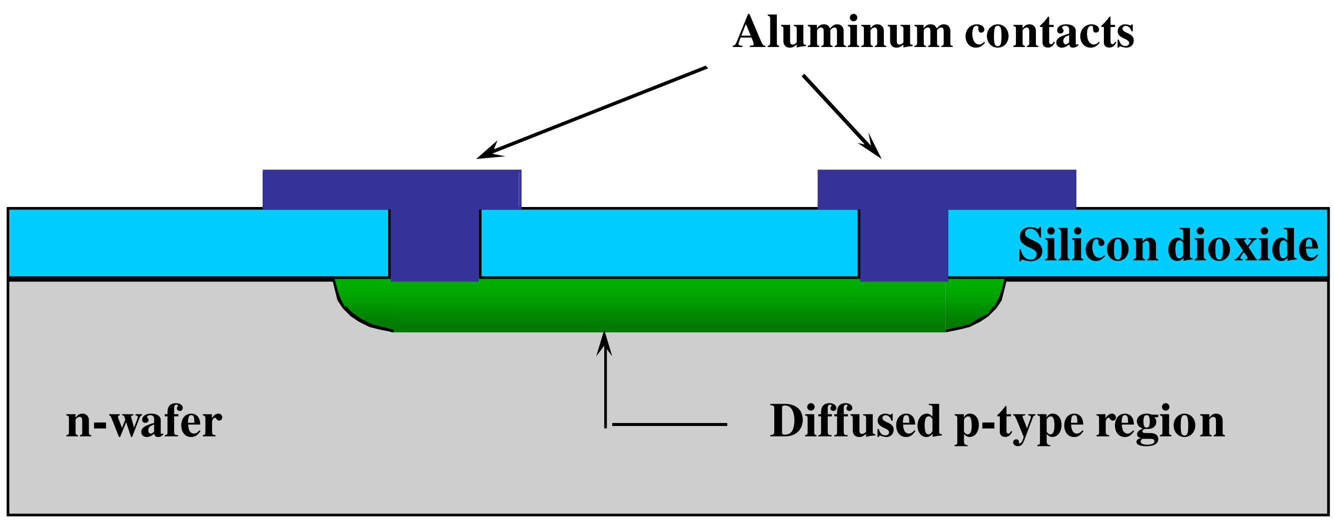
KT/q	0.026	Volts
Eg=Ego-(aT^2/(T+B))	1.115	eV
Nc	2.82E+19	cm-3
Nv	1.34E+01	cm-3
Fermi Level, Ef	0.9295	eV above Ev
free electrons, n = Nc exp(-q(Ec-Ef)KT)	2.17E+16	cm-3
Ionized donors, Nd+ = Nd*(1+2*exp(q(Ef-Ed)/KT))^(-1)	2.97E+16	cm-3
holes, p = Nv exp(-q(Ef-Ev)KT)	3.43E-15	cm-3
Ionized acceptors , Na- = Na*(1+2*exp(q(Ea-Ef)/KT))^(-1)	8.00E+15	cm-3
Charge Balance = p + Nd+ - n - Na-	3.22E+12	cm-3

Click on Button to do Calculation

Button

Roc
Mic

DIFFUSED RESISTOR

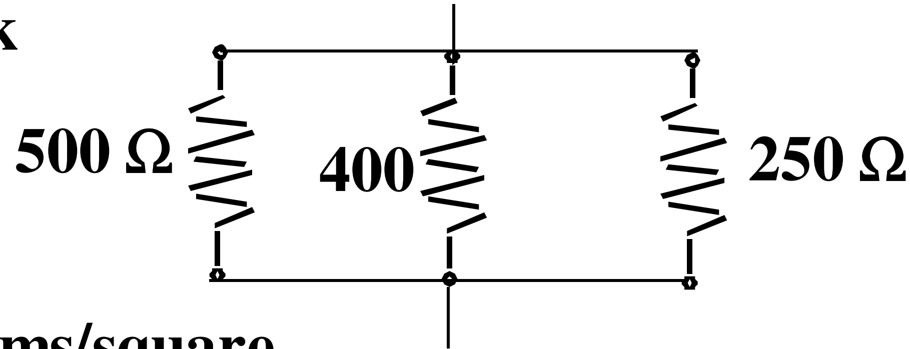


The n-type wafer is always biased positive with respect to the p-type diffused region. This ensures that the pn junction that is formed is in reverse bias, and there is no current leaking to the substrate. Current will flow through the diffused resistor from one contact to the other. The I-V characteristic follows Ohm's Law: I = V/R

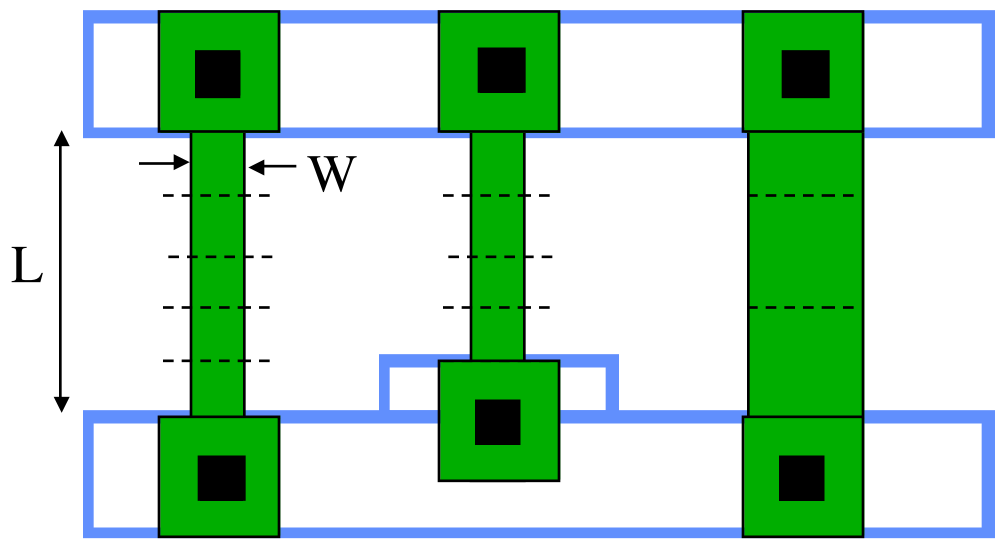
Sheet Resistance $= \rho_s \sim 1/(q\mu \text{ Dose})$ ohms/square

RESISTOR NETWORK

Desired resistor network



Layout if Rhos = 100 ohms/square



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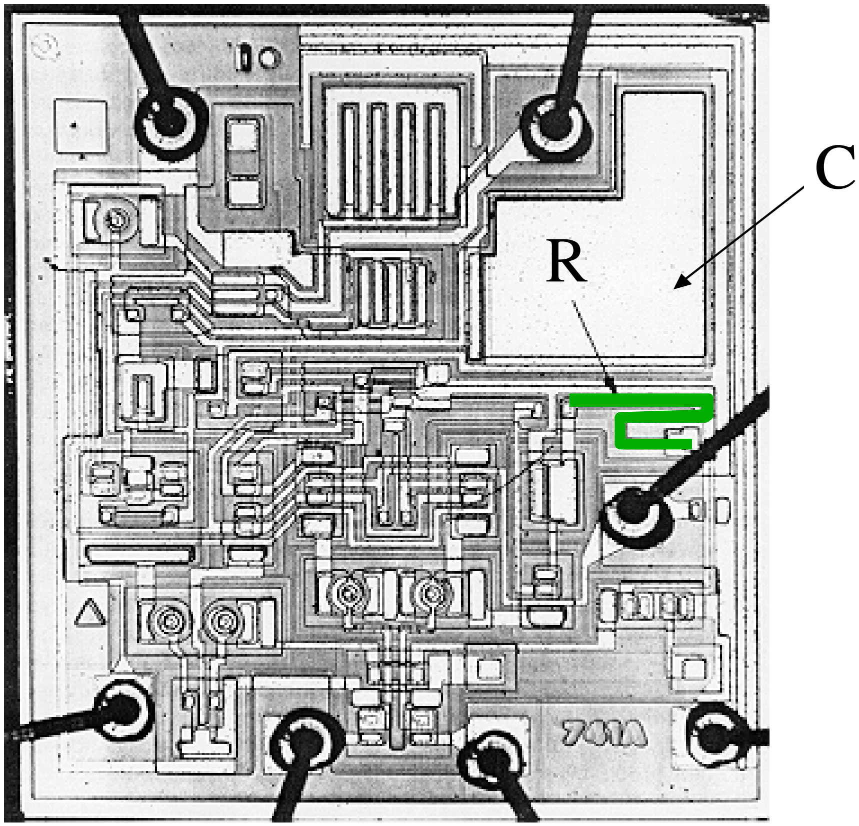
R AND C IN AN INTEGRATED CIRCUIT

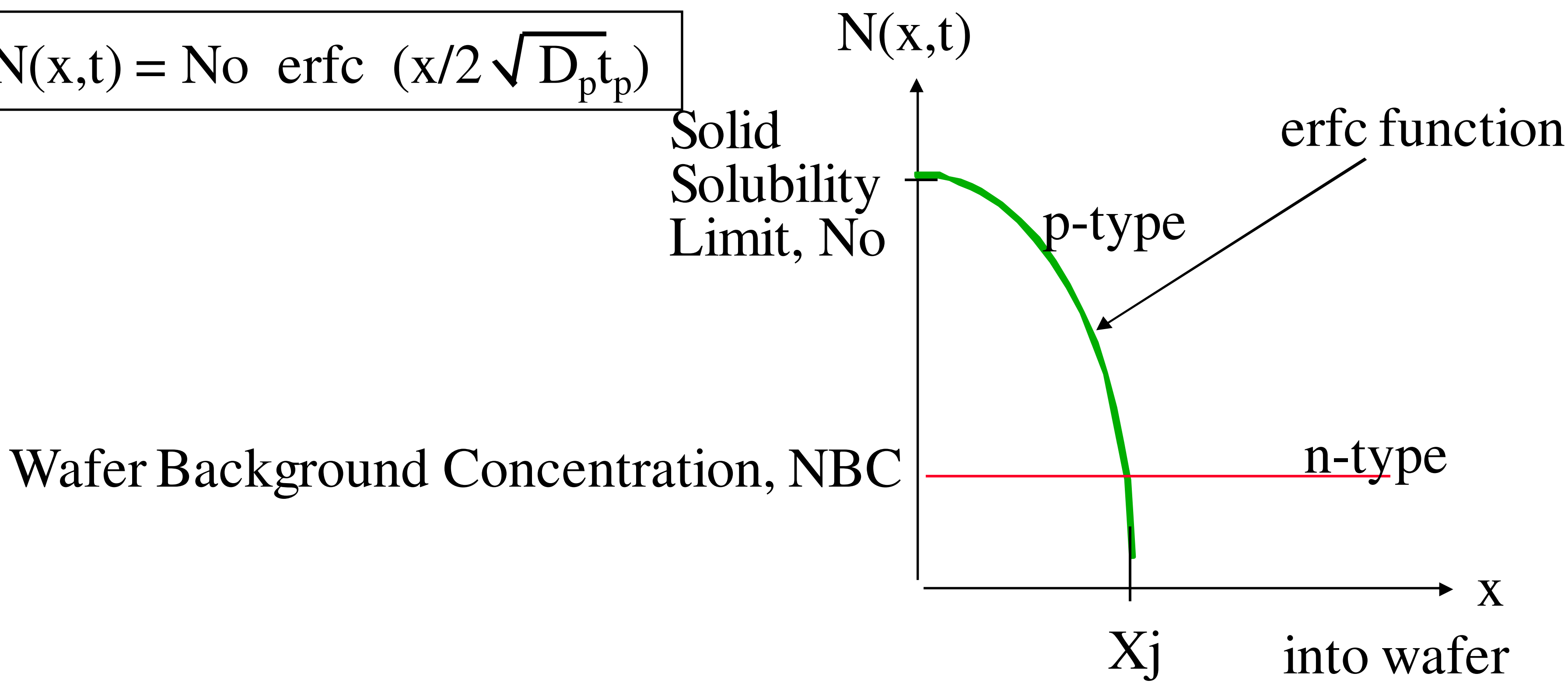
741 OpAmp



Estimate the sheet resistance of the 4000 ohm resistor shown.

DIFFUSION FROM A CONSTANT SOURCE

$N(x,t) = No \ \ erfc \ \ (x/2\sqrt{D_p t_p})$



for erfc predeposit

$$Q'_A\,(tp) = Q_A(tp)/Area = 2\ No\ \sqrt{(Dptp)/\pi} \quad = Dose$$

Where Dp is the diffusion constant at the predeposit temperature and tp is the predeposit time

DIFFUSION FROM A LIMITED SOURCE

$$N(x,t) = \frac{Q'_A(tp)\ \mathrm{Exp}\ (-\,x^2/4Dt)}{\sqrt{\pi\, Dt}}$$

Gaussian function

for erfc predeposit

$$Q'_A\,(tp) = Q_A(tp)/\mathrm{Area} = 2\ No\sqrt{(Dptp)/\pi} \quad = \mathrm{Dose}$$

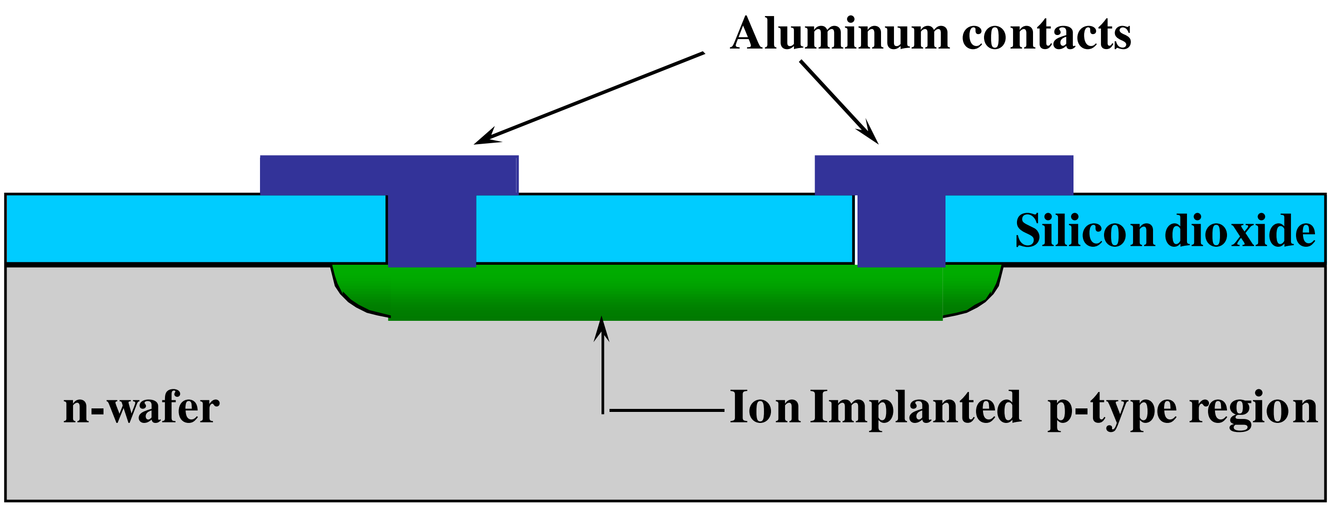
Where D is the diffusion constant at the drive in temperature and t is the drive in diffusion time, Dp is the diffusion constant at the predeposit temperature and tp is the predeposit time

DIFFUSION CONSTANTS AND SOLID SOLUBILITY

DIFFUSION CONSTANTS

TEMP	BORON PRE or DRIVE-IN Dp or D	PHOSPHOROUS PRE Dp	PHOSPHOROUS DRIVE-IN D	BORON SOLID SOLUBILITY NOB	PHOSPHOROUS SOLID SOLUBILITY NOP
900 °C	1.07E-15 cm2/s	2.09e-14 cm2/s	7.49E-16 cm2/s	4.75E20 cm-3	6.75E20 cm-3
950	4.32E-15	6.11E-14	3.29E-15	4.65E20	7.97E20
1000	1.57E-14	1.65E-13	1.28E-14	4.825E20	9.200E20
1050	5.15E-14	4.11E-13	4.52E-14	5.000E20	1.043E21
1100	1.55E-13	9.61E-13	1.46E-13	5.175E20	1.165E21
1150	4.34E-13	2.12E-12	4.31E-13	5.350E20	1.288E21
1200	1.13E-12	4.42E-12	1.19E-12	5.525E20	1.410E21
1250	2.76E-12	8.78E-12	3.65E-12	5.700E20	1.533E21

ION IMPLANTED RESISTOR

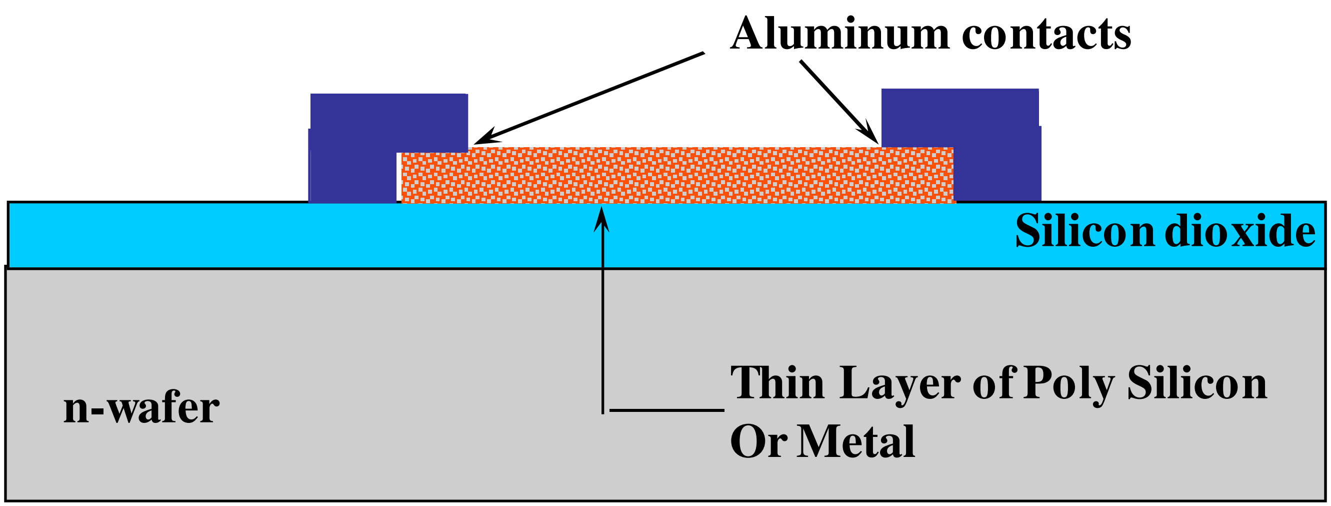


Like the diffused resistor but more accurate control over the sheet resistance. The dose is a machine parameter that is set by the user.

Sheet Resistance $= \rho_s \sim 1/(q\mu \text{ Dose})$ ohms/square

Also the dose can be lower than in a diffused resistor resulting in higher sheet resistance than possible with the diffused resistor.

THIN FILM RESISTOR



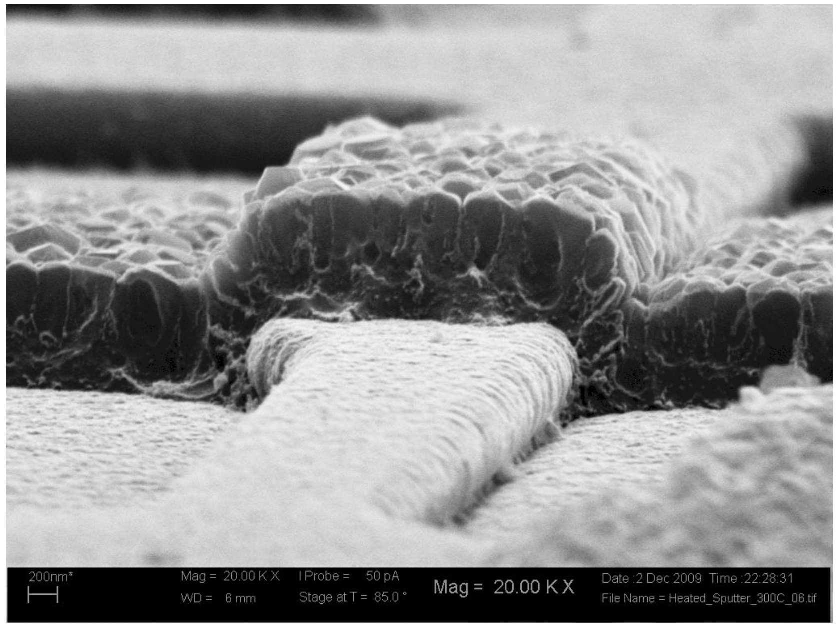
For polysilicon thin films the Dose = film thickness ,t, x Solid Solubility No if doped by diffusion, or Dose ~ 1/2 ion implanter dose setting if implanted

The Sheet Resistance Rhos = ~ 1/(qμ Dose) + Rgrain boundaries ohms/square

For metal the Sheet Resistance is ~ the given (table value) of bulk resistivity, Rho, divided by the film thickness ,t.

Rhos = Rho / t ohms/square

POLY SILICON



Grain boundary take up some of the implanted dose. They also add resistance to the resistor that is less sensitive to temperature and doping concentration. We assume grain size ~ equal to ½ the film thickness (t) and the number of grains equals the path length (L) divided by grain size (t/2). Each grain boundary adds a fixed resistance which is found empirically. (example 0.9 ohms)

CALCULATION OF RESISTANCE

Calculation of Mobility of Single Crystal Silicon

CONSTANTS	VARIABLES			CHOICES	
Tn = T/300 1.00				1=yes, 0=no	
	Temp=	300	°K	n-type	0
	Concentration from Dose / thickness, N = Dose/t =	1.33E+18	cm-3	p-type	1
Kamins, Muller and Chan; 3rd Ed., 2003, pg 33					
	mobility = µ =	131	cm2/(V-sec)		

Calculation of Resistance

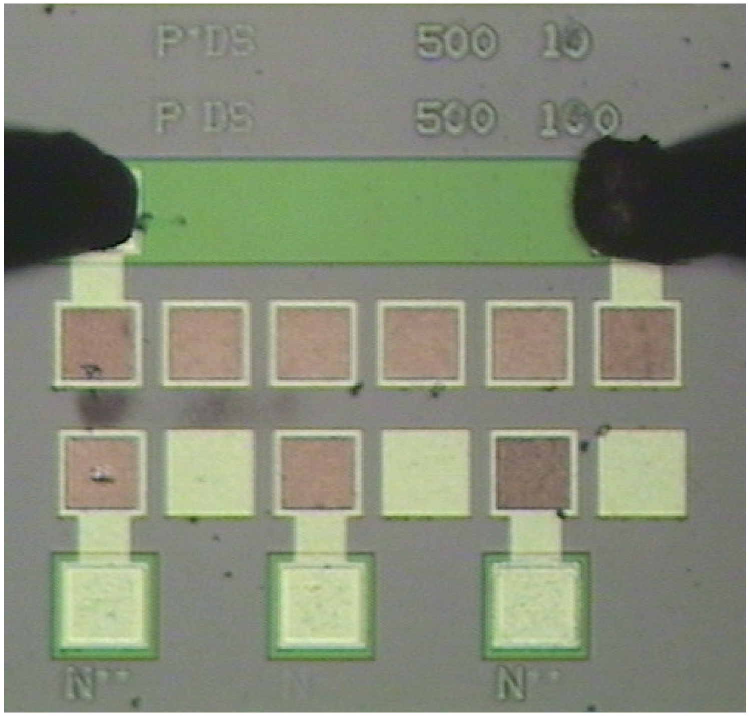
Length is the drawn length	Length, L =	180	µm
Width is the drawn width	Width, W =	200	µm
Thickness is known if poly, or Xj from Diffusion.XLS	Thickness, t =	1.5	µm
Implanter setting if doped by ion implant or from Diffusion.xls if doped by diffusion	Dose =	2.00E+14	/cm2
	Poly ?	0	Yes=1, No=0
	resistance/poly grain boundary	0.9	ohm

Calculation of Resistance

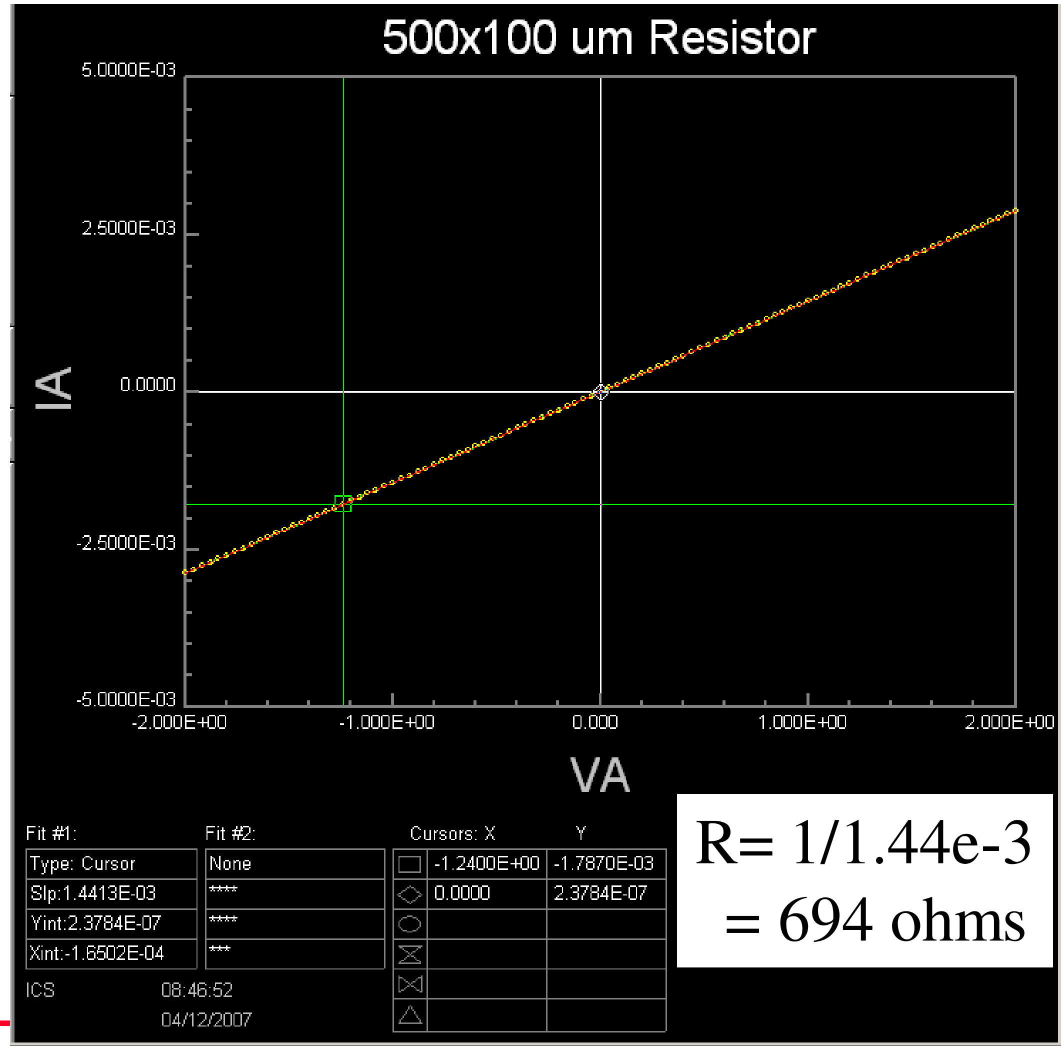
	approximate number of grain boundaries in path = L / t =	120	
	Average Doping = Dose/Thickness =	1.33E+18	atoms/cm3
	Mobility, µ =	131	cm2/v-sec
q = 1.6e-19 coulomb / ion	Rhos = sheet resistance = 1/(q µ Dose) =	239	ohms/sq
	Rho = bulk resistivity =	159	ohm-cm
R = Rho L / W / t	Resistance =	215	ohms
R = Rhos L / W	If Poly the effective sheet resistance =	239	ohms/sq

We assume the grain size is equal to the poly film thickness/2. We calculate the number of grains from the length, L, divided by the grain size, t/2. We also assume the grain boundary adds a fixed resistance that is not a function of temperature or doping. The resistance of a grain boundary is found from resistance measurements of poly resistors.

RESISTOR I-V CHARACTERISTICS

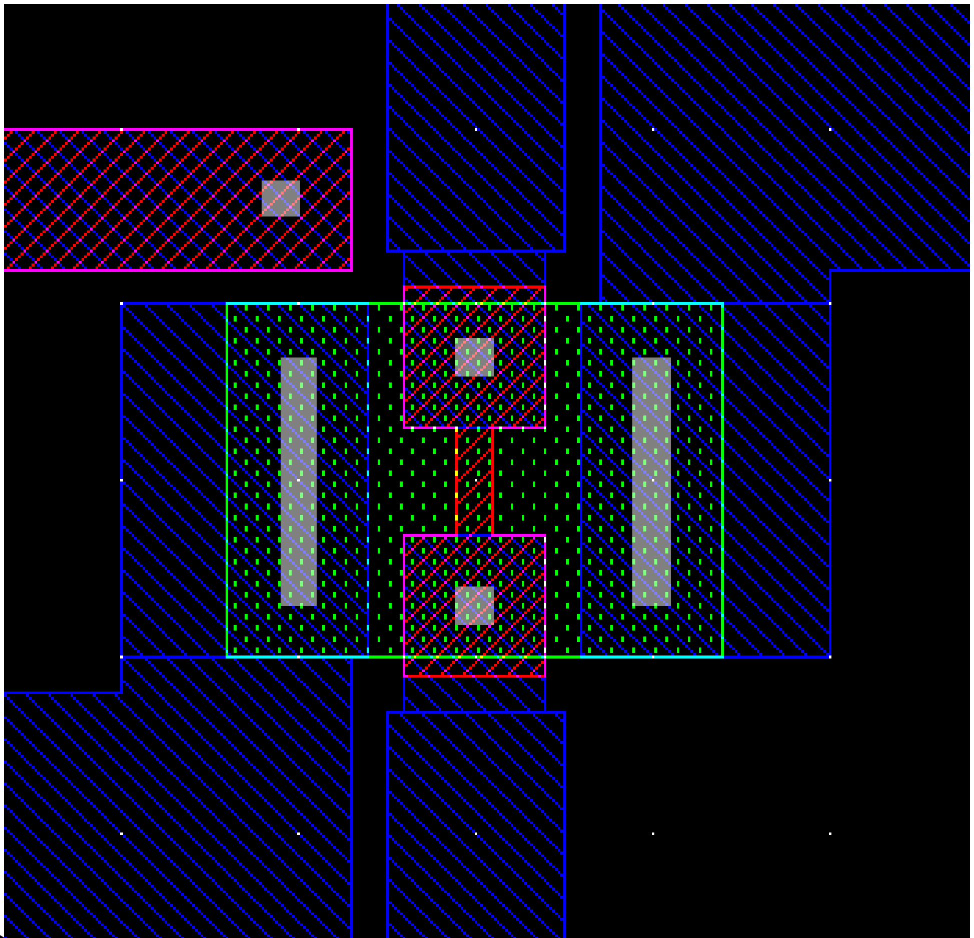


Use t=1.5, L=500, w=100 dose =0.5e15, p-type single crystal silicon



R= 1/1.44e-3
= 694 ohms

CLOSE UP OF RESISTORS AND THERMOCOUPLE



Aluminum – N+ Poly Thermocouple

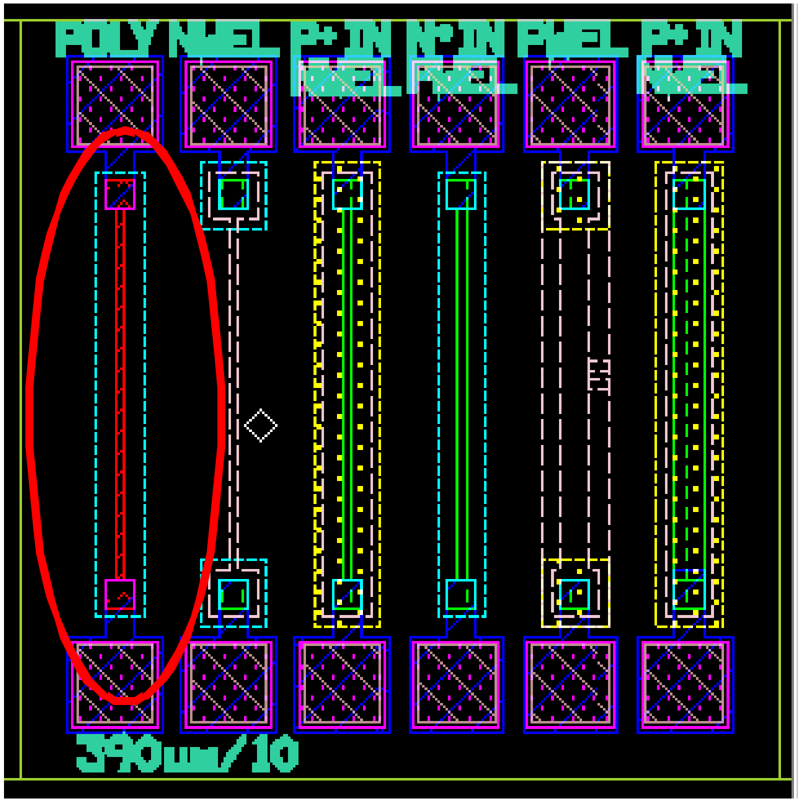
Green P+ Diffused Resistor
200 um wide x 180 um long

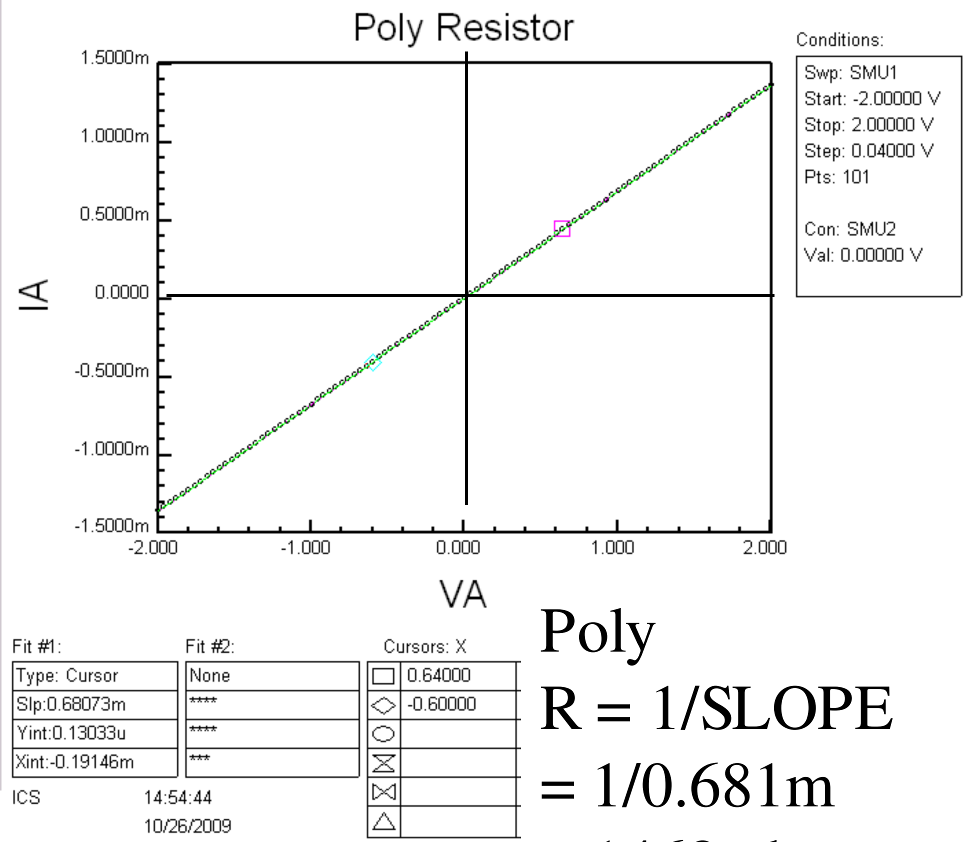
Use t=1.5, L=180, w=200 dose =2e14, p-type crystalline, Rmeas = 207

Red N+ Polysilicon Resistor
60 um x 20 um
+ 30 to contact so L/W ~ 6

Use t=0.5, L=120, w=20 dose =1e16, n-type poly, and 0.9 ohms per boundary Rmeas = 448

POLY RESISTOR





Poly

R = 1/SLOPE

= 1/0.681m

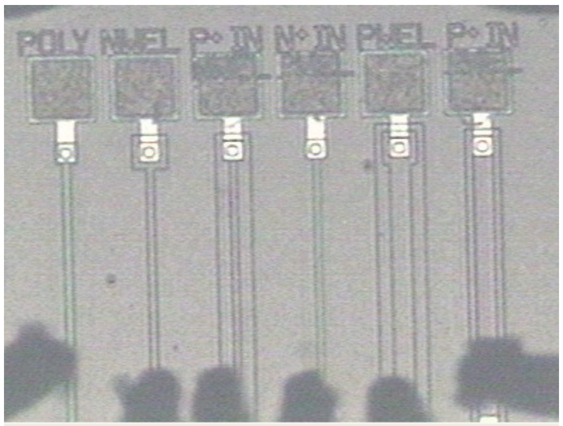
= 1468 ohm

Rhos = 1468/39

=37.6 ohm/sq

Use t=0.6, L=390, w=10
dose =1e16, N-type poly,
and 0.9 ohms per boundary

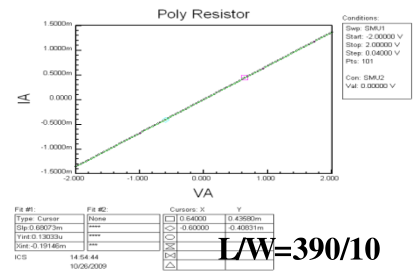
SIX DIFFERENT RESISTORS



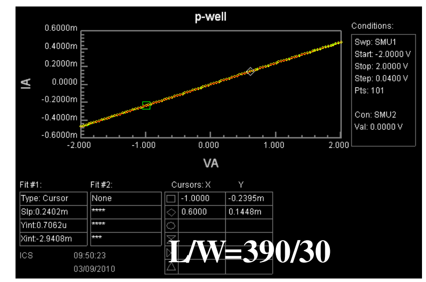
390/10um 390/30um
L/W

R= 1/slope

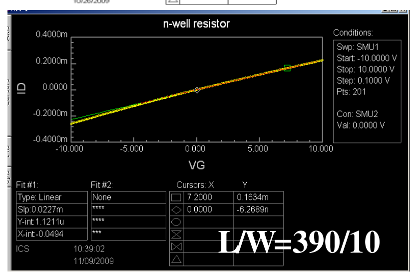
Rhos= R W/L



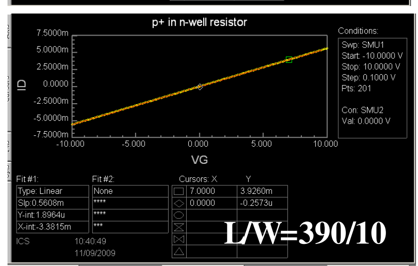
Poly
R=1468
Rhos=37.6



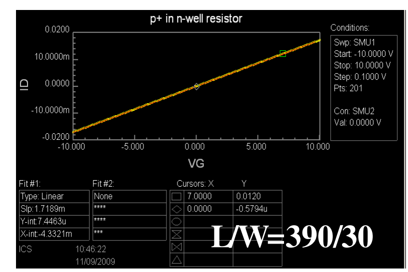
Pwell
R=4160
Rhos=320



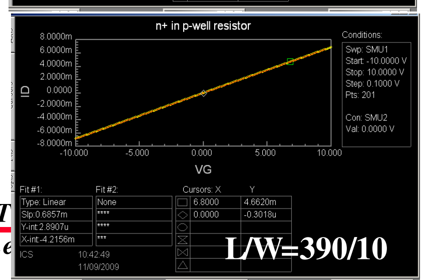
nWell
R=44K
Rhos=1.13K



P+ in nWell
R=1.78K
Rhos=45.7



P+ in nWell
R=582
Rhos=44.8

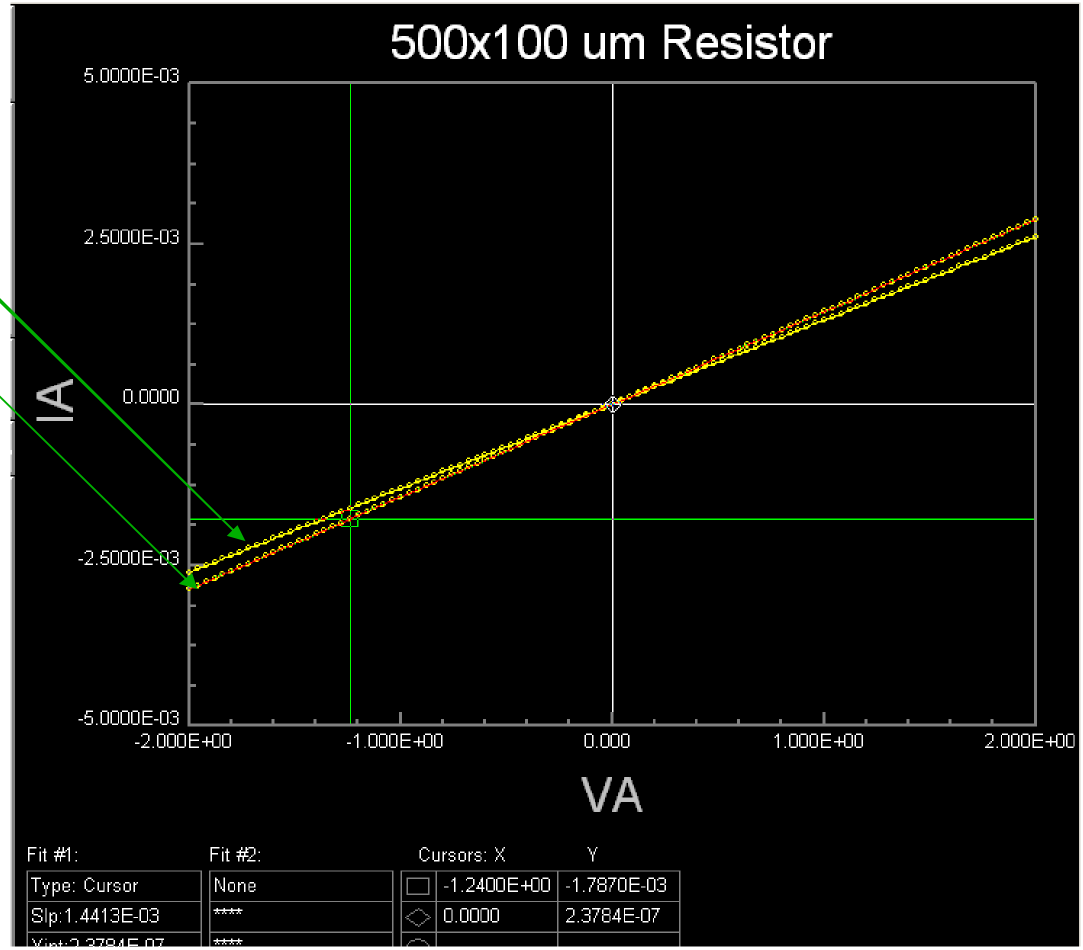


n+ in pWell
R=1.46K
Rhos=37.4

RESISTOR LIGHT RESPONSE

No light

Full light

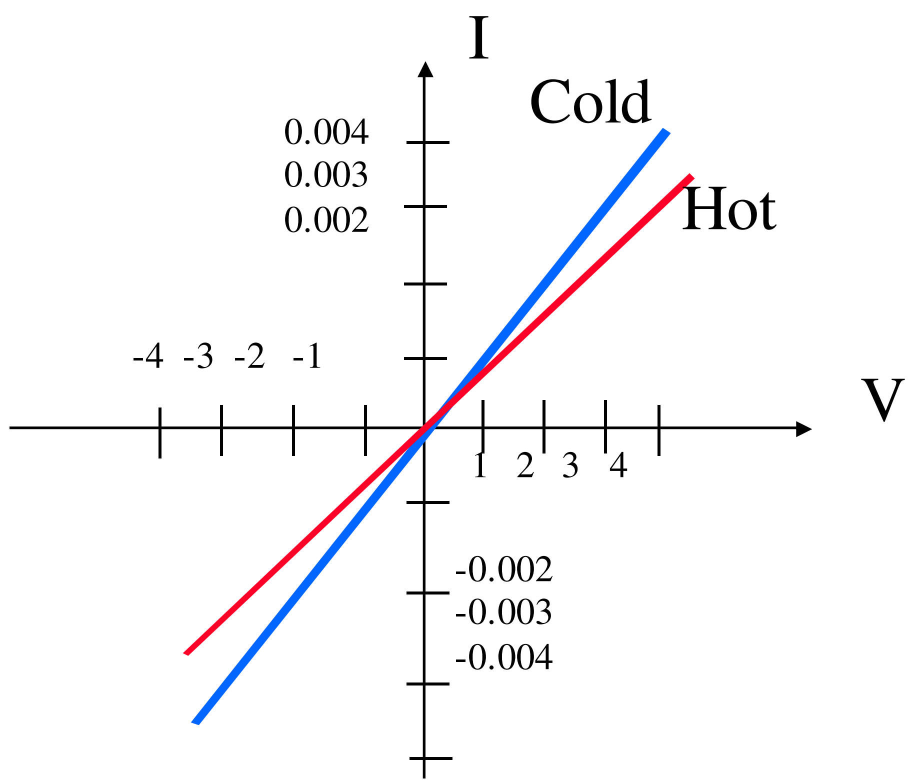


$R = \rho \, L/(W \, xj)$ ohms

$\rho = 1/(\, q\mu_n n + q\mu_p p)$

L,W,xj do not change with light, μn and μp does not change with light but can change with temperature, n and p does not change much in heavy doped semiconductors (that is, n and p is determined by doping)

RESISTOR TEMPERATURE RESPONSE



$R = \rho \, L/(W \, xj)$ ohms

$\rho = 1/(q\mu_n n + q\mu_p p)$

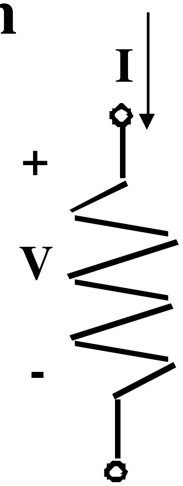
L,W,xj do not change with light, µn and µp does not change with light but can change with temperature, n and p does not change much in heavy doped semiconductors (that is, n and p is determined by doping)

HEATERS

Final steady state temperature depends on power density in watts/cm2

and

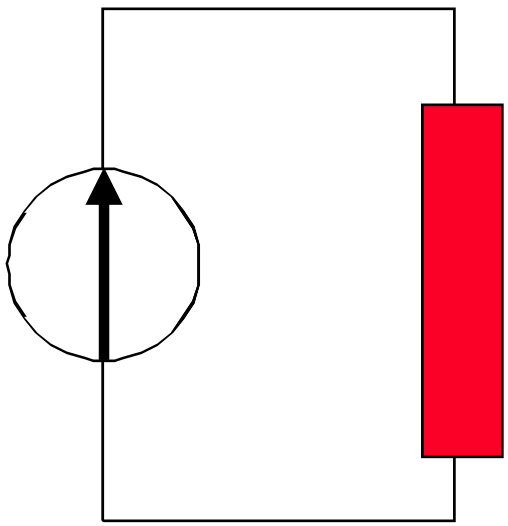
the thermal resistance from heater to ambient



R = ρ_s L/W

$P = IV = I^2R$ watts

THERMAL CONDUCTIVITY



Rth = 1/C L/Area

where

C=thermal conductivity
L= thickness of layer between heater and ambient
Area = cross sectional area of the path to ambient

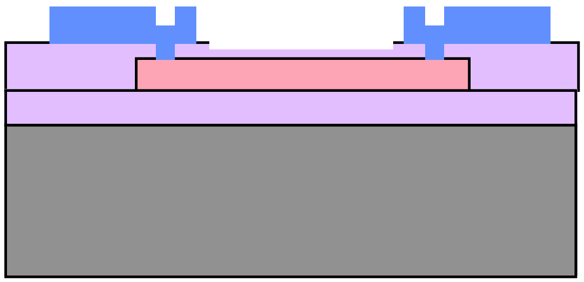
THERMAL PROPERTIES OF SOME MATERIALS

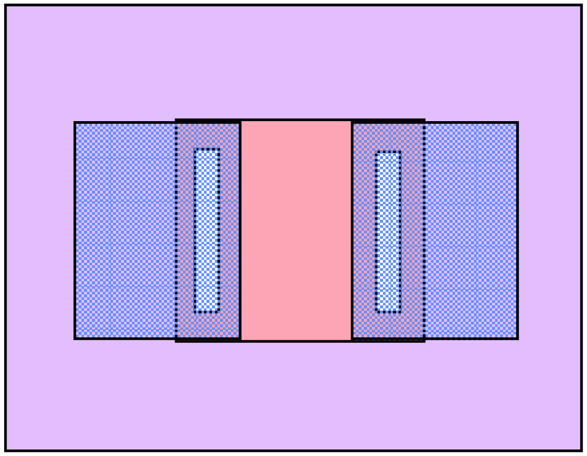
	MP °C	Coefficient of Thermal Expansion ppm/°C	Thermal Conductivity w/cmK	Specific Heat cal/gm°C
Diamond		1.0	20	
Single Crystal Silicon	1412	2.33	1.5	
Poly Silicon	1412	2.33	1.5	
Silicon Dioxide	1700	0.55	0.014	
Silicon Nitride	1900	0.8	0.185	
Aluminum	660	22	2.36	0.215
Nickel	1453	13.5	0.90	0.107
Chrome	1890	5.1	0.90	0.03
Copper	1357	16.1	3.98	0.092
Gold	1062	14.2	0.032	
Tungsten	3370	4.5	1.78	
Titanium	1660	8.9	0.17	
Tantalum	2996	6.5	0.54	
Air			0.00026	0.24
Water	0		0.0061	1.00

1 watt = 0.239 cal/sec

HEATER EXAMPLE

Example: Poly heater 100x100µm has sheet resistance of 25 ohms/sq and 9 volts is applied. What temperature will it reach if built on 1 µm thick oxide?





Power $= V^2/R = 81/25 = 3.24$ watt

$R_{thermal}$ = 1/C L/Area = (1/0.014 watt/cm °C)(1e-4cm/(100e-4cm x100e-4cm))
= 71.4 °C/watt

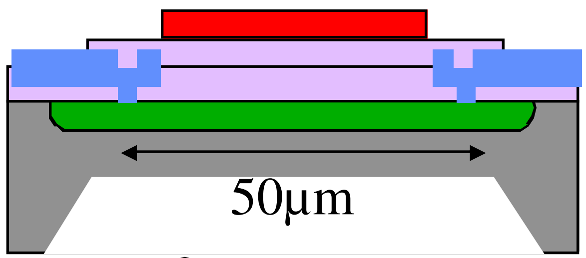
Temperature $= T_{ambient} + (3.24)\ (71.4) = T_{ambient} + 231\ °C$

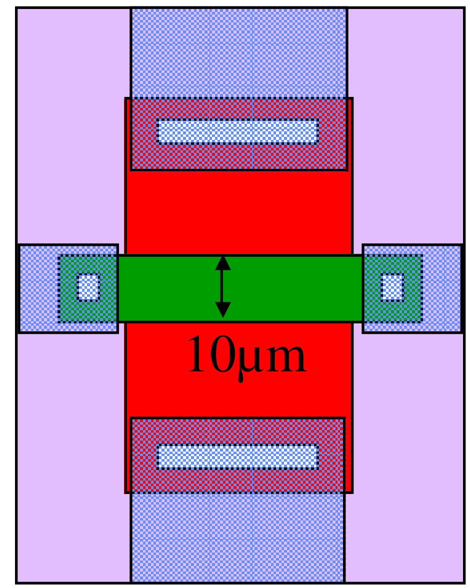
TEMPERATURE SENSOR EXAMPLE

Example: A poly heater is used to heat a sample. The temperature is measured with a diffused silicon resistor. For the dimensions given what will the resistance be at 90°C and 65°C

$x_j = t = 1\mu m$

$N_d = n = 1E18 cm^{-3}$





$$R(T,N) = \frac{1}{q\,\mu_n(T,N)\,n}\;\frac{L}{Wt}$$

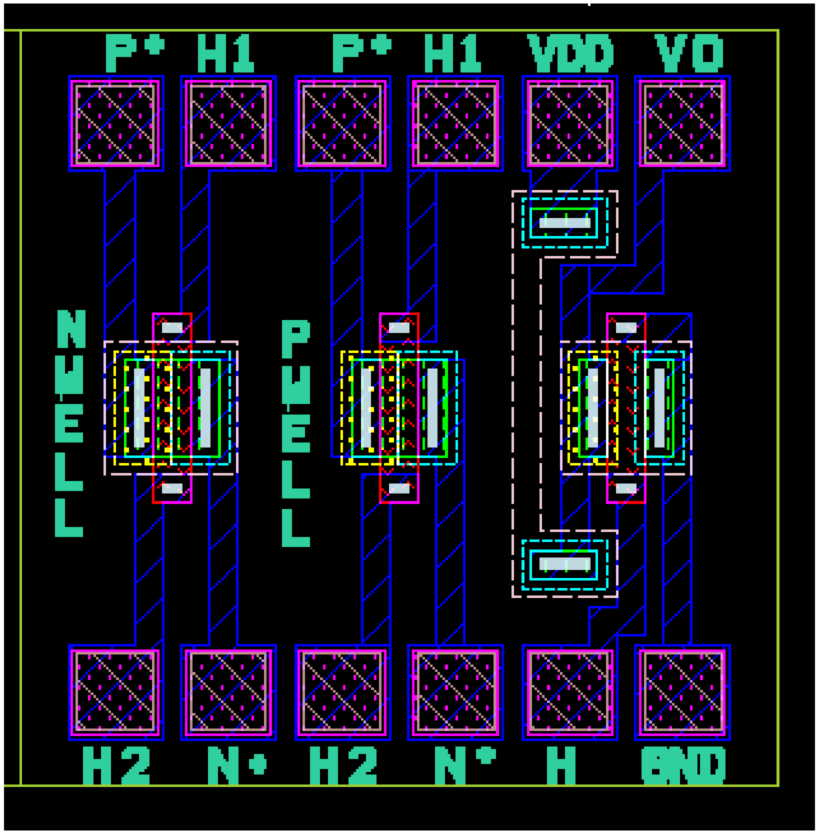
(L/Wt → 50,000)

$q\,\mu_n\,(T=273+90=363, N=1e18)\,n = 1.6e\text{-}19\,(165)\,1e18 = 22.6$ R=1892 ohms

$q\,\mu_n\,(T=273+65=338, N=1e18)\,n = 1.6e\text{-}19\,(196)\,1e18 = 26.1$ R=1593 ohms

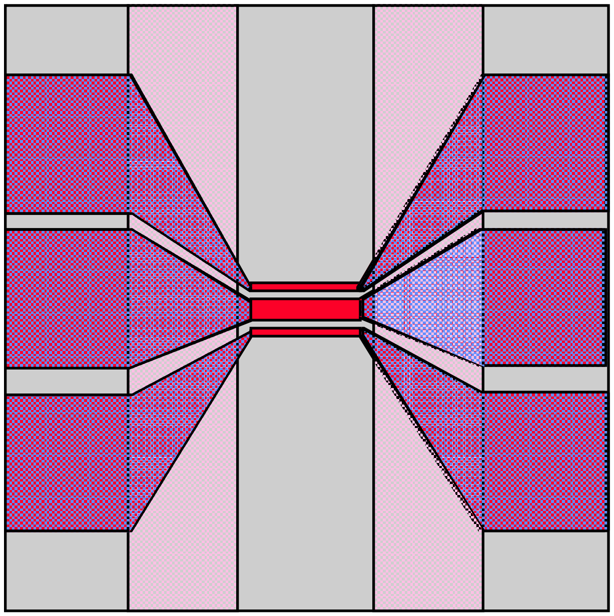
DIODES AND HEATERS

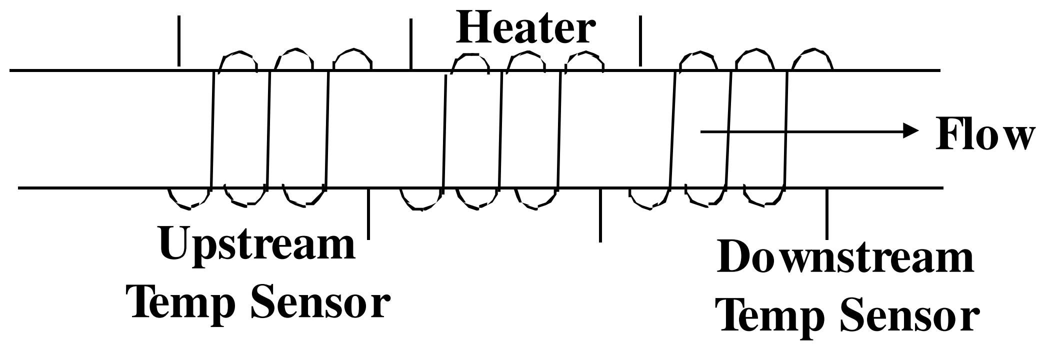
Poly Heater on top of Diodes

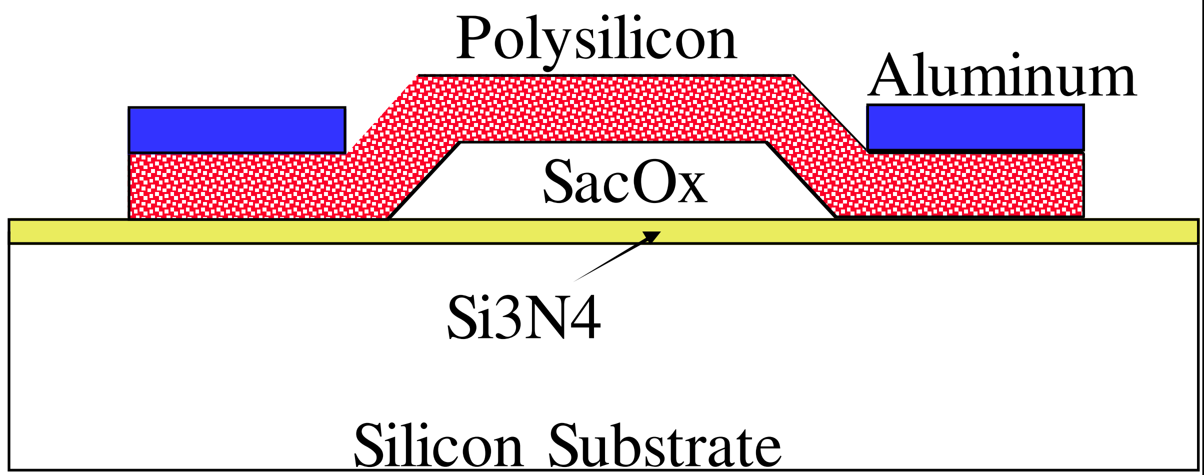


Integrated series resistor.

THERMAL FLOW SENSORS

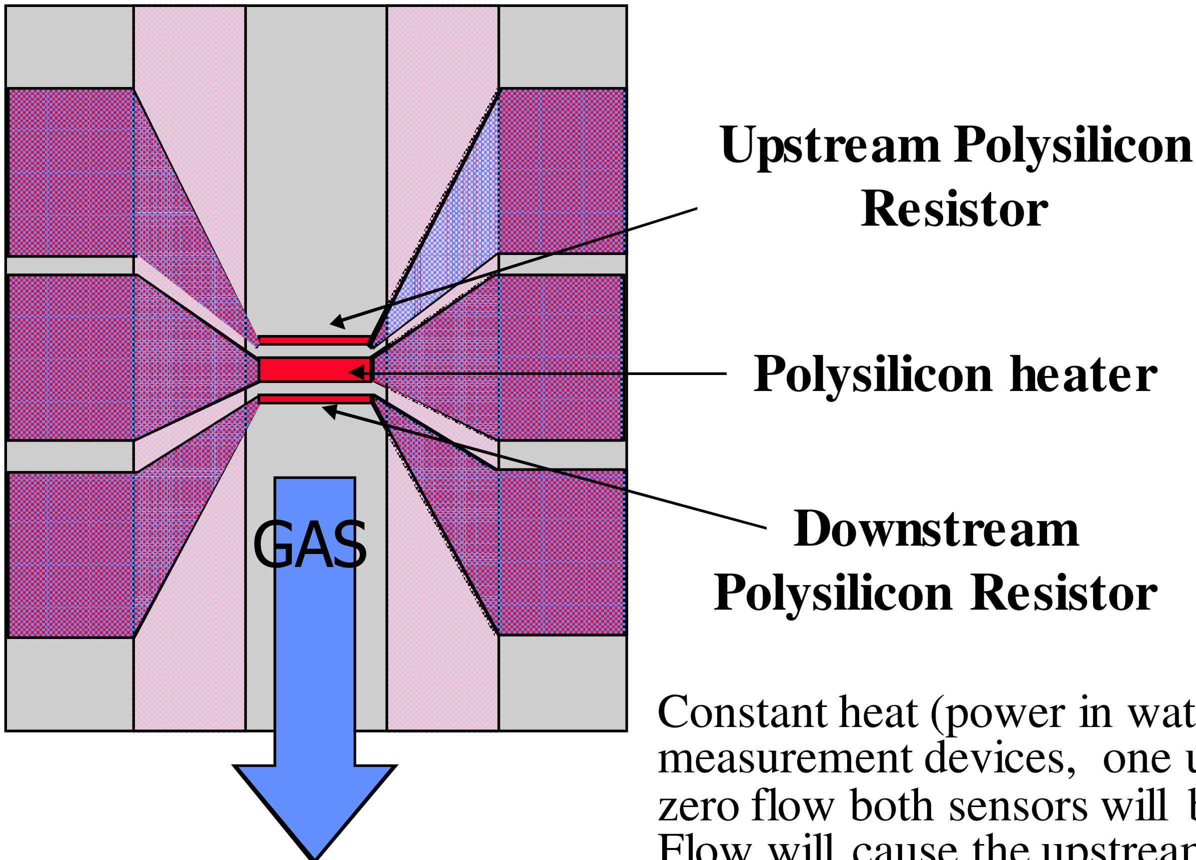






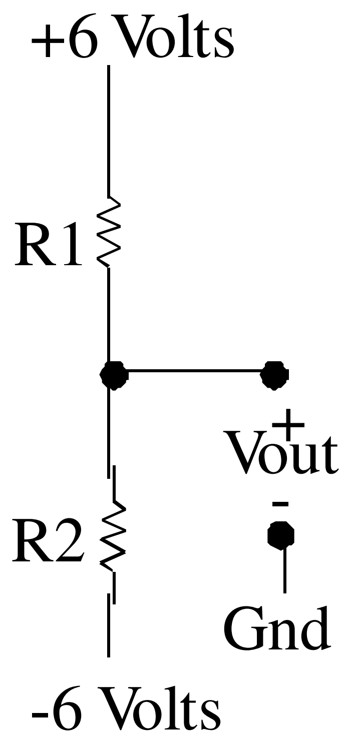
Spring 2003
EMCR 890 Class Project
Dr. Lynn Fuller

GAS FLOW SENSORS

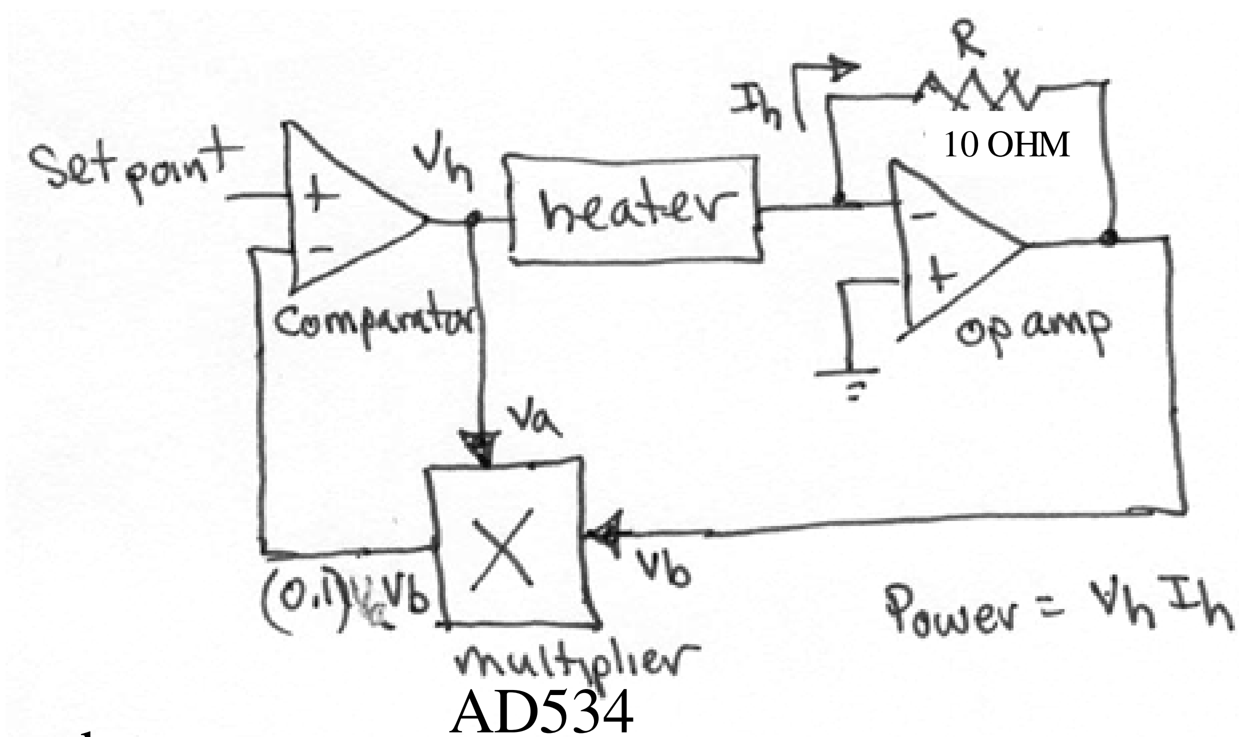


Constant heat (power in watts) input and two temperature measurement devices, one upstream, one downstream. At zero flow both sensors will be at the same temperature. Flow will cause the upstream sensor to be at a lower temperature than the down stream sensor.

FLOW SENSOR ELECTRONICS



Constant Power Circuit



Vout near Zero so that
it can be amplified

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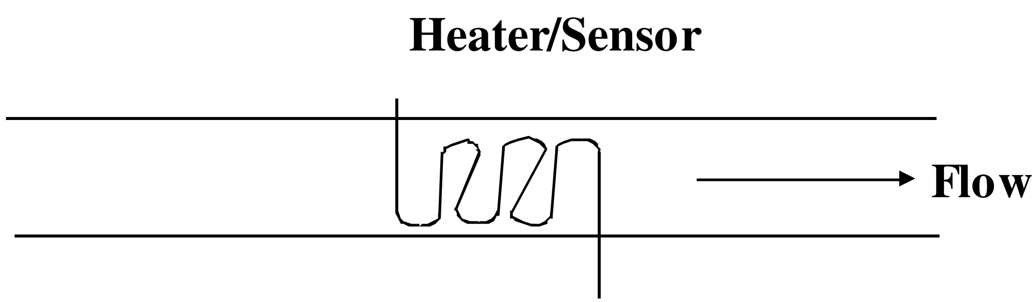
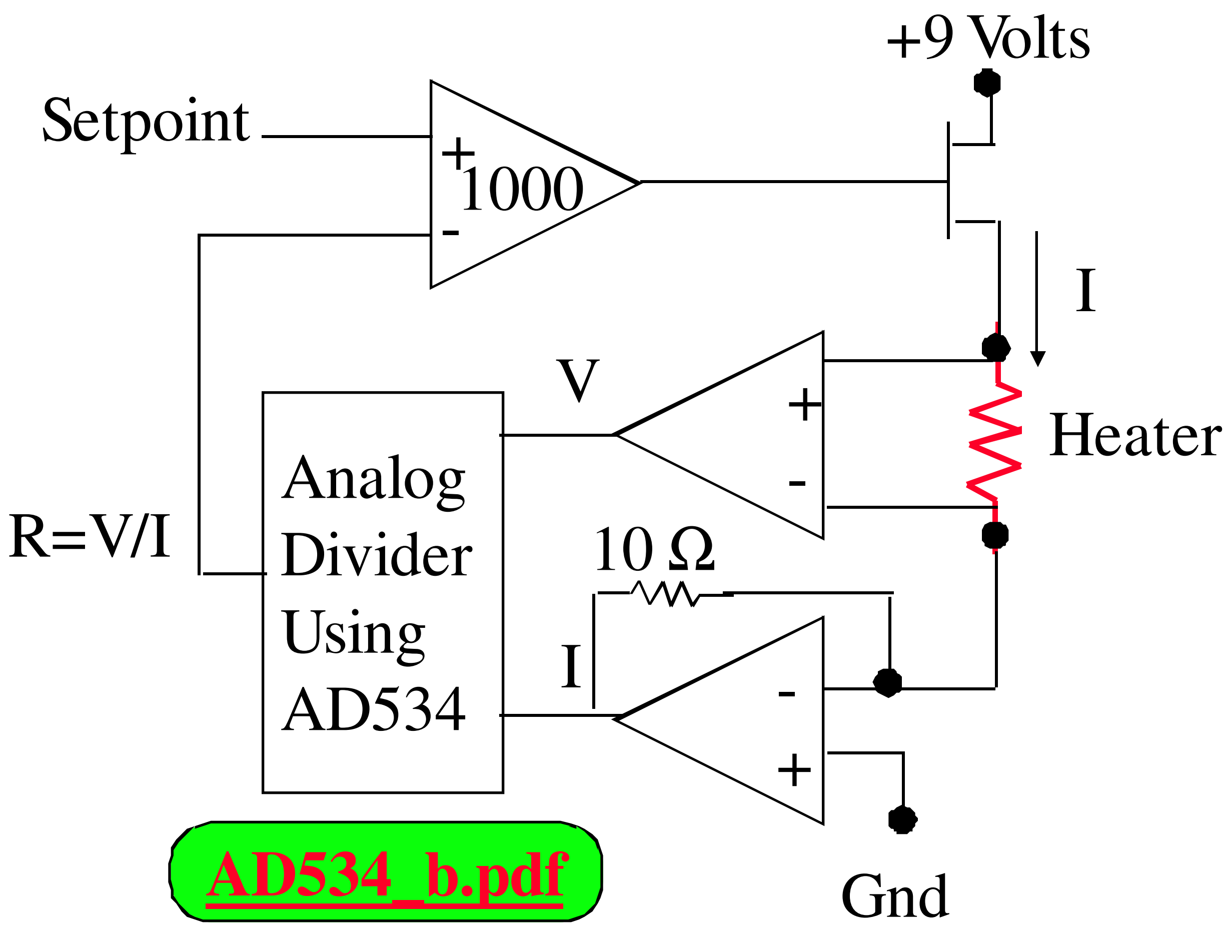
SINGLE WIRE ANEMOMETER

A single heater/sensor element is placed in the flow. The amount of power supplied to keep the temperature constant is proportional to flow. At zero flow a given amount of power Po will heat the resistor to temperature To. With non zero flow more power Pf is needed to keep the resistor at To.



CONSTANT TEMPERATURE CIRCUIT



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HOMEWORK – RESISTORS

1. Poly heater is 500 µm long and 100µm wide, it has a sheet resistance of 25 ohms/sq and 9 volts is applied. What temperature will it reach if built on 1000Å of silicon nitride on top of 10,000Å thick oxide?

2. A diffused resistor is used as a temperature sensor. Calculate what the resistance will be at room T and at 150 °C above room T. The diffused resistor is 1000 µm long and 20 µm wide. It has an average Boron doping (Na) of 1E16 cm-3 over its 2.5 µm thickness.