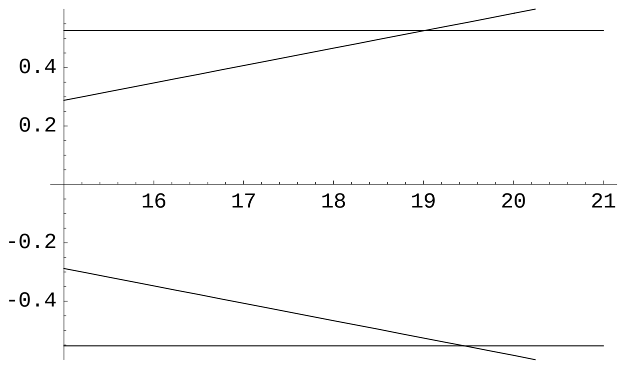
■ Characteristics of MOSFET using MATHEMATICA
Lecture : Information Devices
15 March 2005 Nagoya University Prof. K.Nakazato

Initialize : set constants

```
Clear["Global`*"];
Off[General::spell]; Off[General::spell1];
<< "Graphics`Graphics`"
(* constants *)
q = 1.60218 × 10^-19   (* elementary charge [C] *);
k = 1.38066 × 10^-23   (* Boltzman constant [J/K] *);
T = 300               (* Absolute temperature [K] *);
ni = 1.45 × 10^10      (* intrinsic carrier concentration [cm-3] *);
e0 = 8.85418 × 10^-14  (* permitivity in vaccum [F/cm] *);
es = 11.9 e0          (* silicon permitivity *);
eox = 3.9 e0          (* oxide permitivity *);
Nc = 2.8 × 10^19       (* effective density of state in conduction band [cm-3] *);
Nv = 1.04 × 10^19      (* effective density of state in valance band [cm-3] *);

(* input parameters *)
p0 = 2 × 10^17         (* substrate acceptor concentration [cm^-3]*);
tox = 10^-6           (* gate oxide thickness [cm]*);

(* substrate property *)
n0 = ni^2 / p0;                         (* donor concentration [cm^-3]*);
LD = Sqrt[(k T es) / (p0 q^2)];         (* Debye length *)
Ec = k T / q Log[Nc / n0];              (* conduction band edge *)
Ev = -k T / q Log[Nv / p0];             (* valance band edge *)
Ei = (Ec + Ev) / 2 + k T / (2 q) Log[Nv / Nc]; (* intrinsic energy *)

(* gate oxide prperty *)
Cox = eox / tox;                        (* gate capacitance per unit area *)
```

Fermi potential

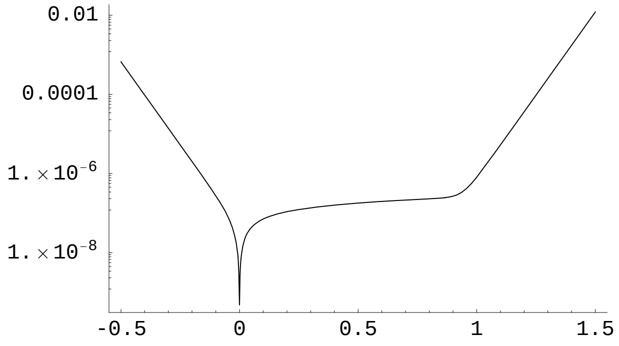
```
Plot[{-k T/q ArcSinh[10^N/(2ni)],k T/q ArcSinh[10^N/(2ni)],Ei-Ec,Ei-Ev},{N,15,21},PlotRang
```



Semiconductor Charge Qs as a function of surface potential p

```
F[x_, y_] := Sign[x] Sqrt[Exp[-x]+x-1 + y(Exp[x] - x - 1)];
Ex[p_,n0_]:= Sqrt[2] k T/q/LD F[q p/(k T), n0/p0];
Qs[p_,n0_]:=-es Ex[p,n0];

Print["P0=",N[p0]," [cm-3]\tEc=",Ec," [eV]\tEi=",Ei," [eV]\tEv=",Ev," [eV]"];
LogPlot[Abs[Qs[p,n0]], {p, -0.5, 1.5}];
```

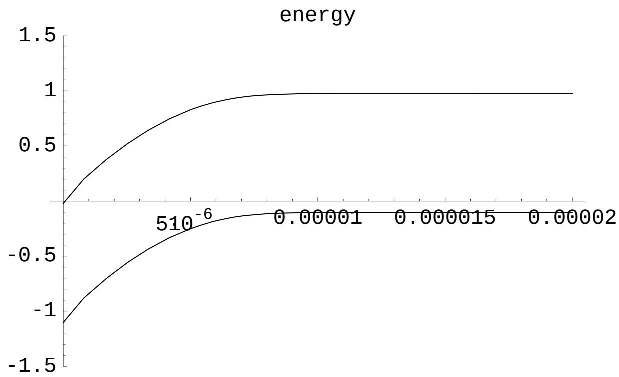
P0=2. × 10^{17} [cm−3]   Ec=0.977754 [eV]   Ei=0.425001 [eV]   Ev=−0.102148 [eV]

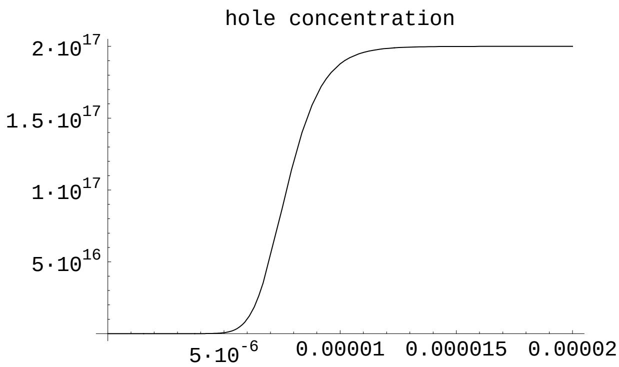


Energy profile : ps is surface potential

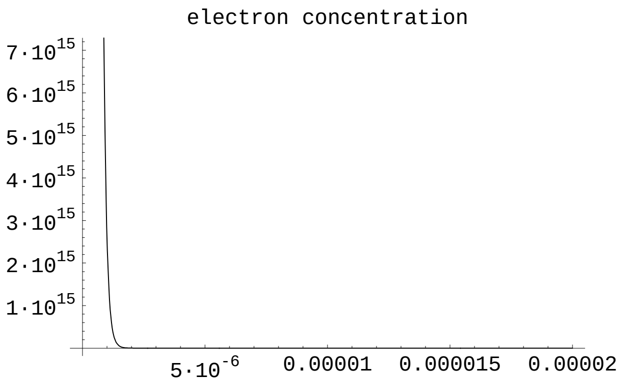
```
ps = 1  (* [V] *);
xmax = 2 × 10^-5; (* [cm] *)

Print["LD=", LD];
eval = NDSolve[{p'[x] + Ex[p[x], n0] == 0, p[0] == ps}, p, {x, 0, xmax}];
Plot[{Evaluate[Ec - p[x] /. eval], Evaluate[Ev - p[x] /. eval]},
  {x, 0, xmax}, PlotRange → {-1.5, 1.5}, PlotLabel → "energy"];
Plot[Evaluate[p0 Exp[-q p[x] / k / T] /. eval], {x, 0, xmax},
  PlotLabel -> "hole concentration"];
W[p_] := -NIntegrate[1 / Ex[x, n0], {x, p, k T / q Log[2]}];
Print["Depletion width=", W[ps]];
Plot[Evaluate[n0 Exp[q p[x] / k / T] /. eval],
  {x, 0, xmax}, PlotLabel -> "electron concentration"];
```

LD=9.21988 × 10^{-7}



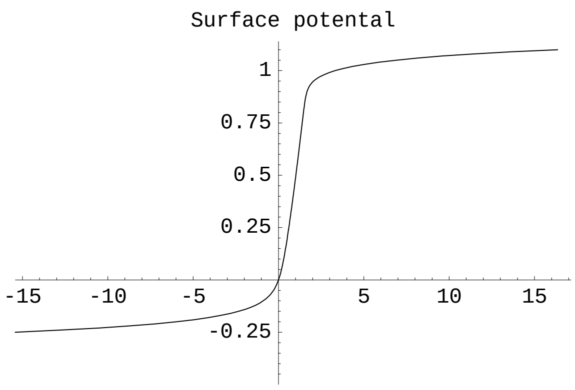


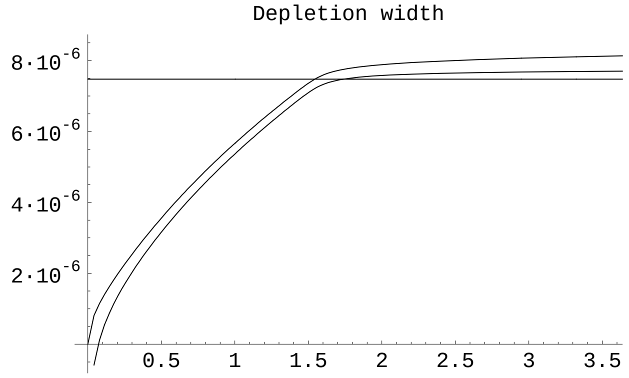
Depletion width=7.69378 × 10^{-6}



Surface potential as a function of gate voltage

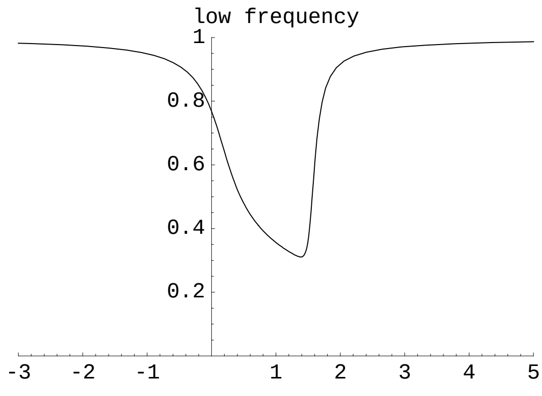
```
Vg[p_,n0_]:=-Qs[p,n0]/Cox + p;

pstart=-0.46; pend=1.1; pstep=0.01;
ListPlot[Table[{Vg[p,n0],p},{p,pstart,pend,pstep}],PlotJoined→True,PlotLabel→"Surface pot

(*depletion width *)
Pl1=ListPlot[Table[{Vg[p,n0],Sqrt[2es p/(q p0)]},{p,0,pend,pstep}],PlotJoined→True,Displa
Off[NIntegrate::singd]; Off[NIntegrate::inum]; Off[Graphics::gptn];
Pl2=ListPlot[Table[{Vg[p,n0],W[p]},{p,0,pend,pstep}],PlotJoined→True,DisplayFunction→Ident
Pl3=ListPlot[Table[{Vg[p,n0],2Sqrt[es Ei/q/p0]},{p,0,pend,pstep}],PlotJoined→True,Display
Show[{Pl1,Pl2,Pl3},DisplayFunction→$DisplayFunction,PlotLabel→"Depletion width"];
```

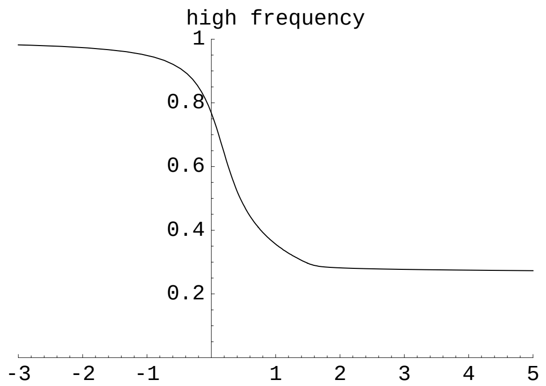


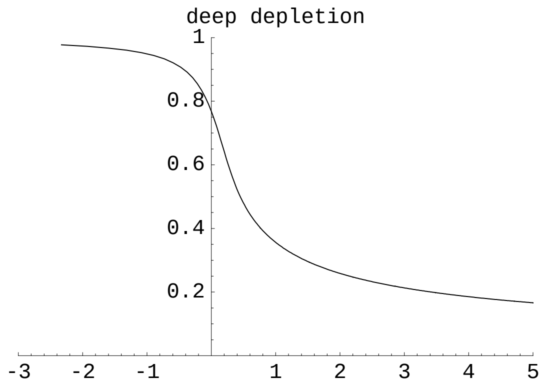


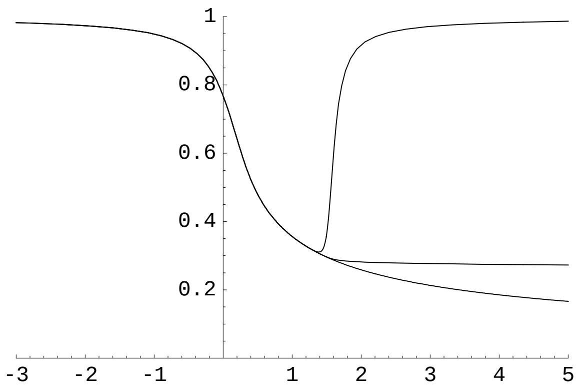
MOS capacitance

```
Fc[x_,y_]:=If[Abs[x]<10^-8,Sqrt[2(1+y)],(-Exp[-x]+1+y(Exp[x]-1))/F[x,y]];
Cs[p_,n0_]:=es/LD Fc[(q p)/(k T), n0/p0]/Sqrt[2];

pstart=-0.25; pend=1.2; pstep=0.01;
Plcl=ListPlot[Table[{Vg[p,n0],1/(Cox/Cs[p,n0]+1)},{p,pstart,pend,pstep}],PlotJoined→True,

pstart=-0.25; pend=1.2; pstep=0.01;
Plch=ListPlot[Table[{Vg[p,n0],1/(Cox/Cs[p,0]+1)},{p,pstart,pend,pstep}],PlotJoined→True,P

pstart=-0.15; pend=4;
Plcd=ListPlot[Table[{Vg[p,0],1/(Cox/Cs[p,0]+1)},{p,pstart,pend,pstep}],PlotJoined→True,Pl

Show[{Plcl,Plch,Plcd},PlotLabel->""];
```









Thredshold voltage

```
PhiF[p_] := Module[{n, LD, Ec, Ev},
  n = ni^2 / p;
  LD = Sqrt[(k T es) / (p q^2)];
  Ec = k T / q Log[Nc / n];
  Ev = -k T / q Log[Nv / p];
  (Ec + Ev) / 2 + k T / 2 Log[Nv / Nc]
 ]
VT[p_] := PhiF[p] + Sqrt[2 q p es 2 PhiF[p]] / Cox;
Plot[VT[10^p], {p, 14, 18}, PlotRange → {0, 3}];
```