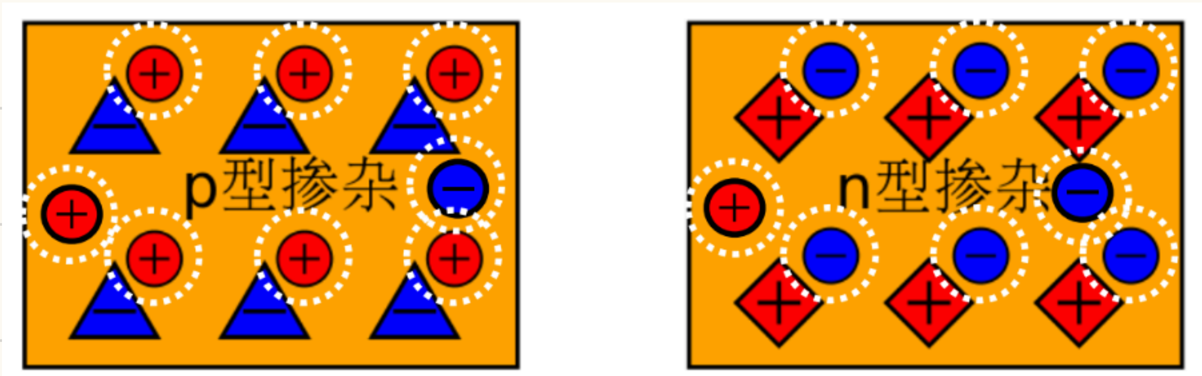
PN结

PN结

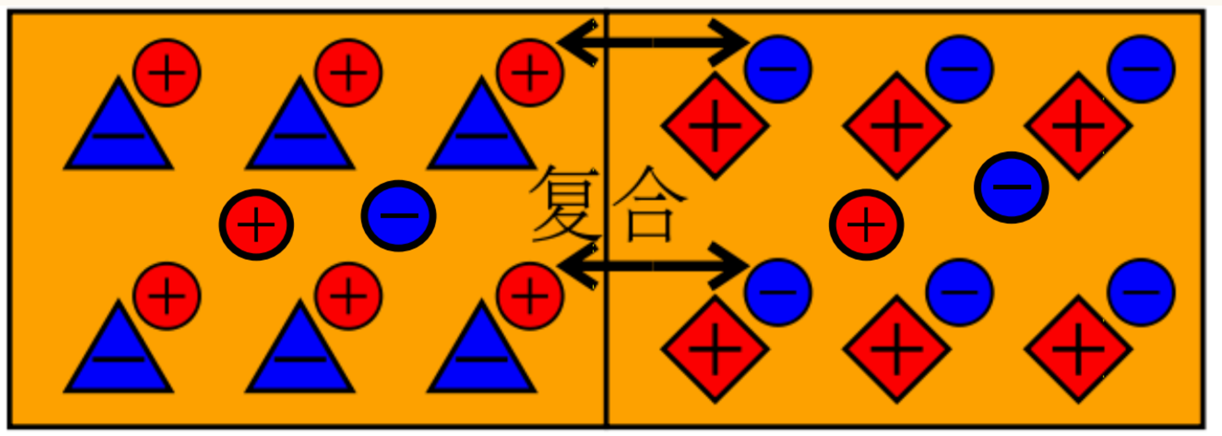
Definition: A P-N junction is formed when an n-type material is fused together with a p-type material creating a semiconductor diode.

定义：当N型材料与P型材料融合在一起形成半导体二极管时，形成P-N结。

图示

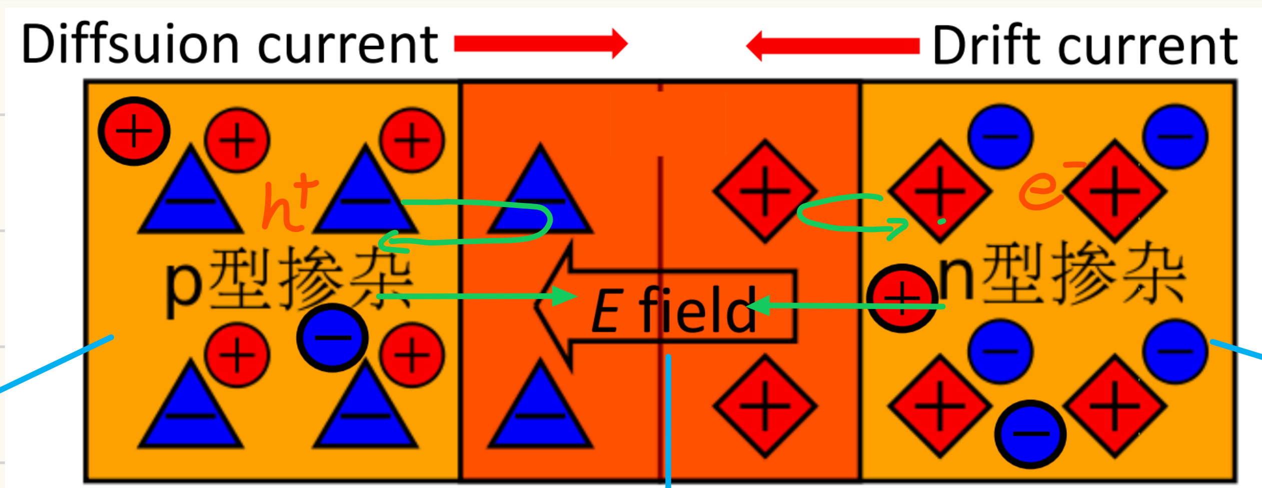


混合前：，P型材料：阴离子+多数空穴+少数电子，N型材料：阳离子+少数空穴+多数电子



混合过程中：P端：空穴向右扩散，N端：电子向左扩散

结：e- h+复合



准中性区

准中性区

耗尽层

混合后：

(1) 结：内建电场

(2) 热平衡时：扩散电流与漂移电流平衡

关于PN结，我们应该了解什么

- What happens when we join p-type and n-type semiconductors?
  当我们连接p型和n型半导体时会发生什么?
- What is the width of the depletion region? How does it relate to the dopant concentration?
  耗尽区的宽度是多少? 它与掺杂剂浓度有何关系?
- What is the built-in voltage? How to calculate it based on dopant concentrations?
  内建电压是多少? 如何根据掺杂浓度计算内建电压?
- What happens when we apply voltage to the P-N junction?
  当我们对 P-N 结施加电压时会发生什么?
- What is the current-voltage characteristic for the P-N junction diode? Why is it different from a resistor?
  P-N结二极管的电流-电压特性是什么? 为什么它与电阻不同?

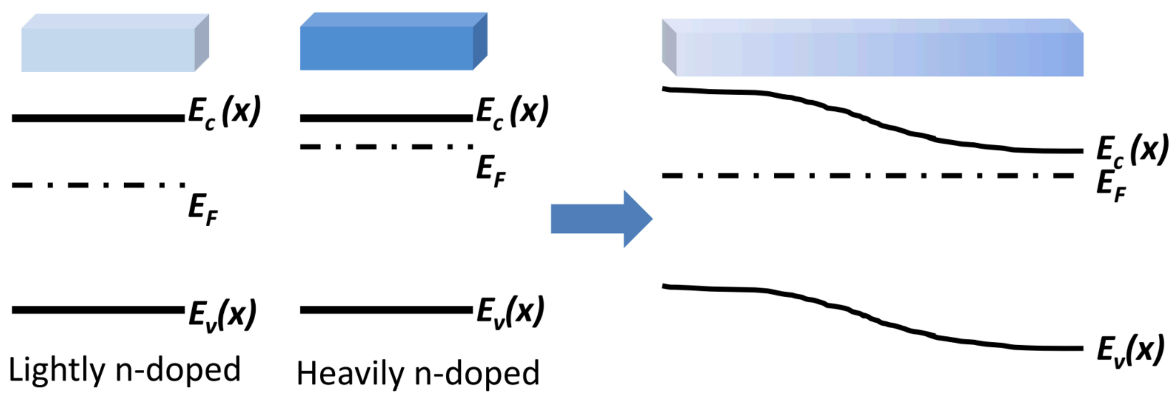
PN结的能带模型

回顾非均匀N型掺杂半导体的能带模型

- **The position of E_F relative to the band edges is determined by the carrier concentrations.**
- **In equilibrium E_F is constant.**

热平衡状态下，费米能级保持水平

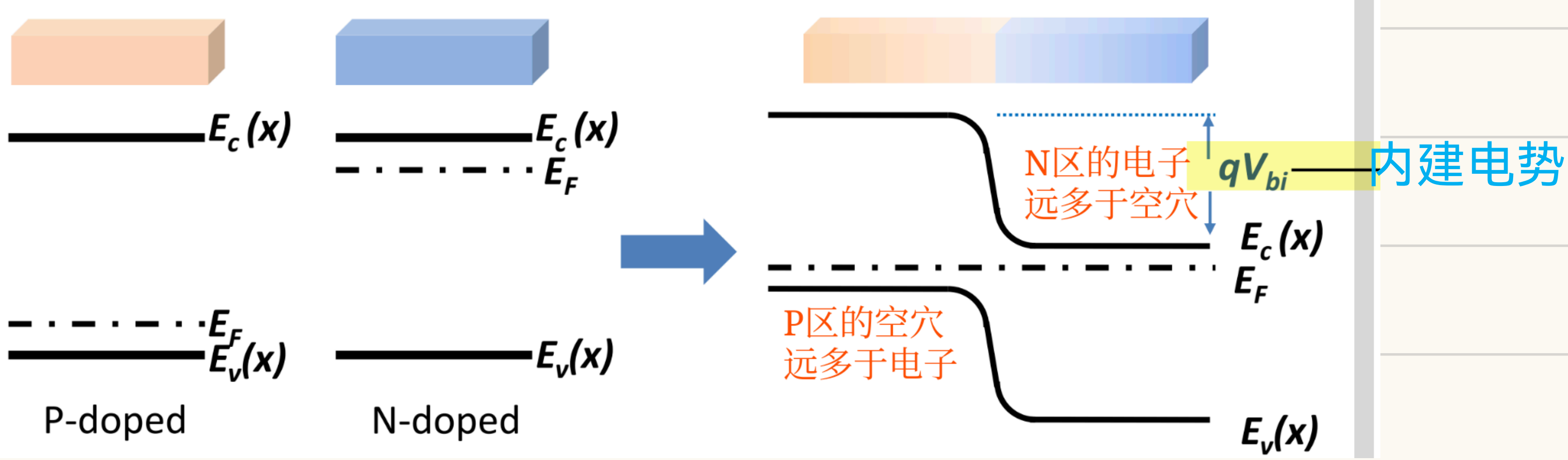
能带与费米能级的距离反映载流子浓度



PN结的能带模型

- **The position of E_F relative to the band edges is determined by the carrier concentrations.**
- **In equilibrium E_F is constant.**

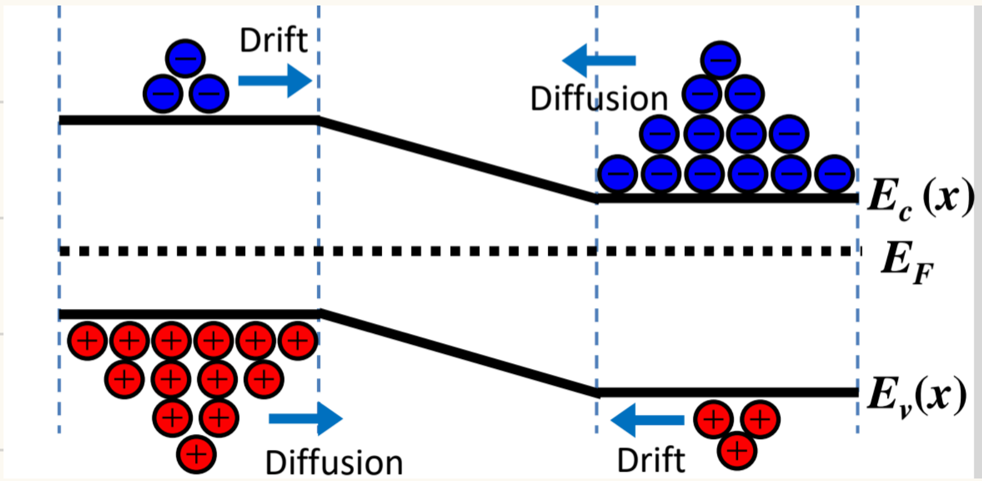
远离结区的位置：P型材料和N型材料的载流子浓度基本维持原样



(1) 扩散：Doped charge carriers diffuse along the carrier concentration gradient.

(2) 漂移：Donor/Acceptor ions stay fixed to form a built-in electric field

(3) 热平衡时：At equilibrium, the diffusion current is compensated by the drift current.



在平衡状态下，扩散电流和漂移电流相互抵消。

Fabrication of the P-N Junction

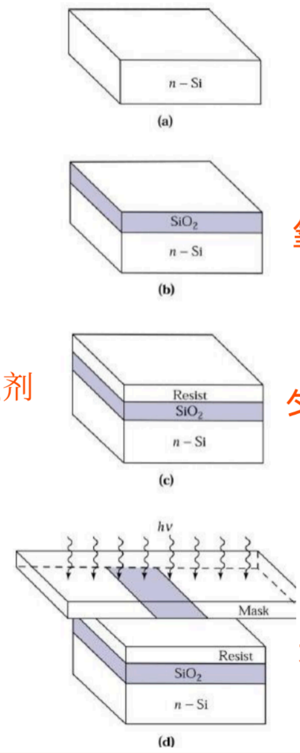
a). A bare n-type Si Wafer

b). Coat thin film SiO_2 on top by dry or wet oxidation

c). Coat photoresist/E-beam resist on SiO_2 在SiO2上涂覆光致抗蚀剂/E束抗蚀剂

使用荫罩进行光刻或直接进行电子束光刻

d). Use shadow mask to do photolithography or directly do E-beam lithography （光刻）



氧化

匀胶

光刻

a). Remove the resist by development. 显影

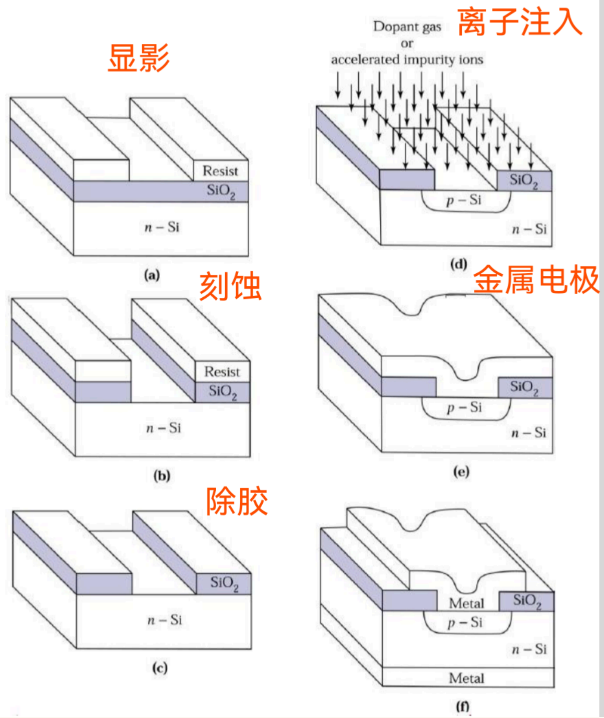
b). Etch SiO_2

c). Lift-off the rest part of resist

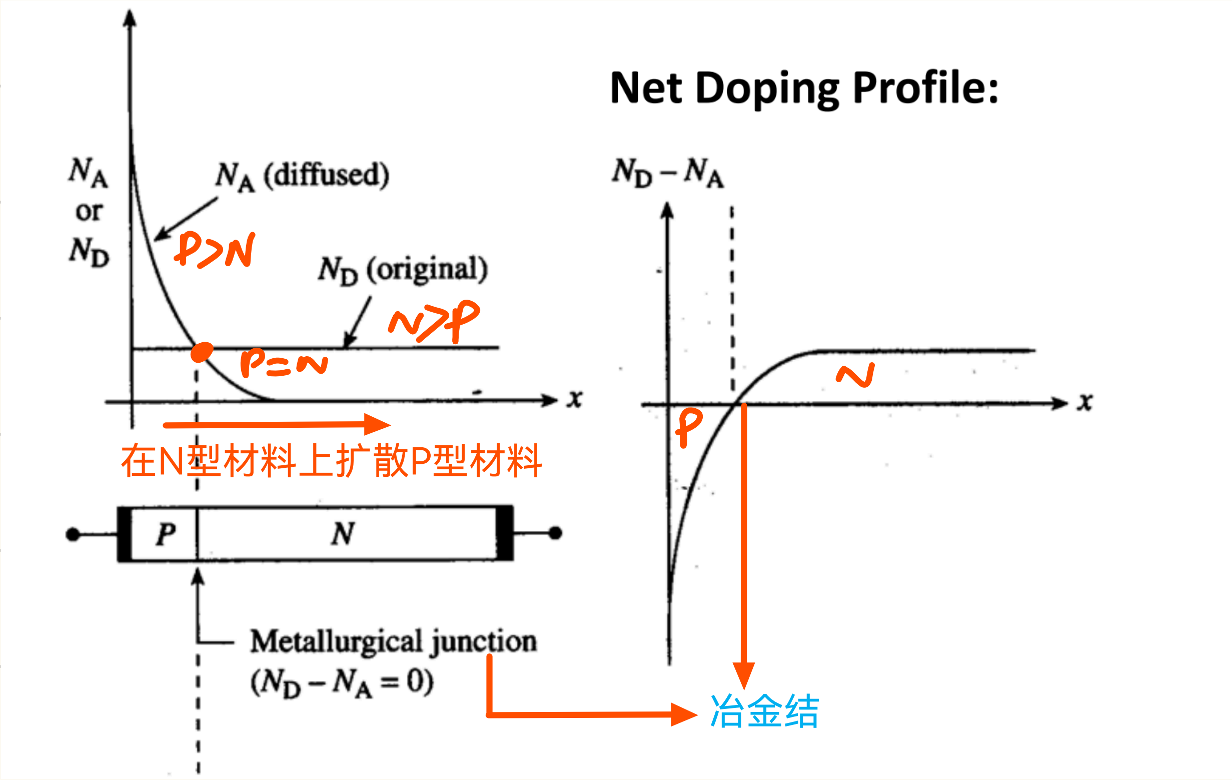
d). Inject p-doping through diffusion or implantation.

e). Metallization

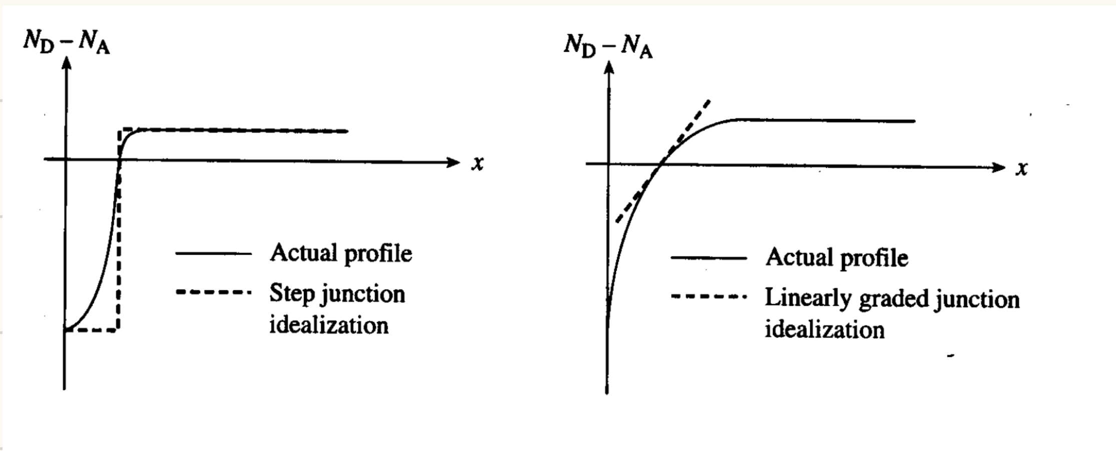
f). A complete P-N junction device



数学描述



两种不同类型的结



Step/Abrupt junction 突变结

轻掺杂的原始晶片上进行浅结扩散

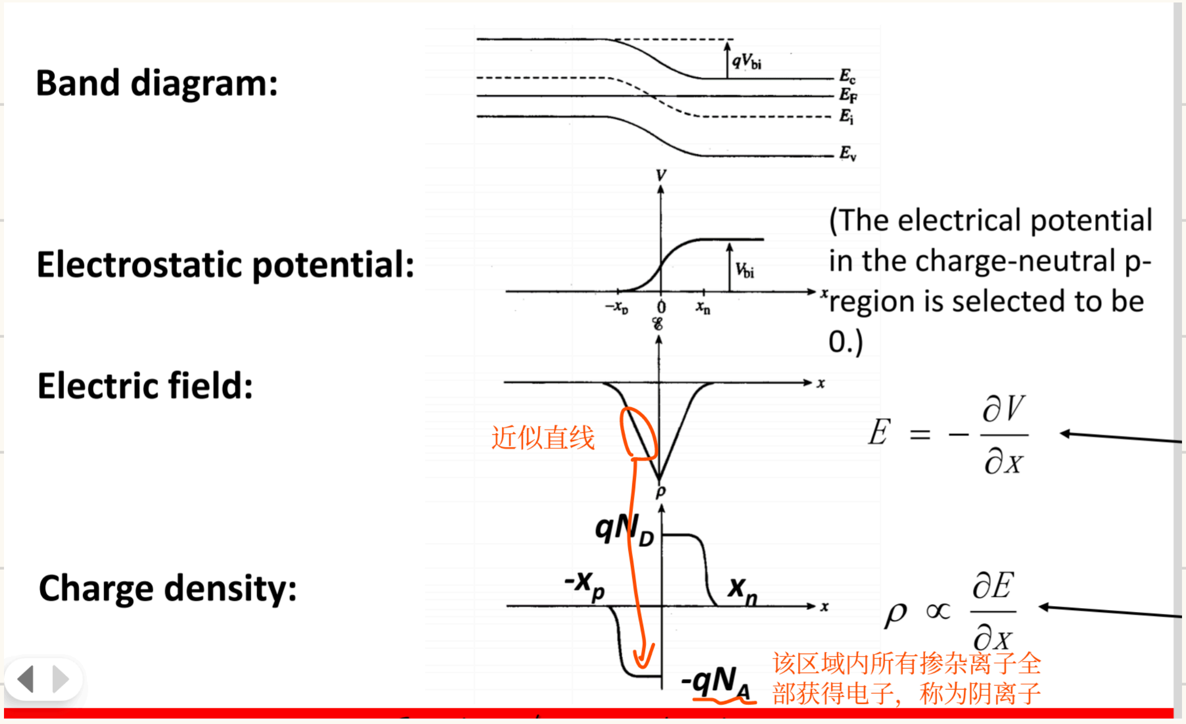
Linearly graded junction 线性缓变结

中、重掺杂的原始晶片上进行深结扩散

本章主要突变结为例介绍

PN结的内建电场

PN结的内建电场——模型图



在接下来的内容中，我们将从载流子的输运理论以及基本电磁学知识出发，逐步推演出上述模型

内建电势Vbi

$$V_{bi} = \frac{kT}{q}\ln\frac{N_D N_A}{n_i^2}$$

推导方法1.

热平衡时，无净电流： $J_N = qn\mu_n E + qD_n\frac{dn}{dx} = 0$

解得电场强度： $E = -\frac{D_n}{\mu_n}\cdot\frac{1}{n}\cdot\frac{dn}{dx}$

爱因斯坦关系式： $\frac{D_n}{\mu_n} = \frac{kT}{q}$ 　　对任何PN结都成立

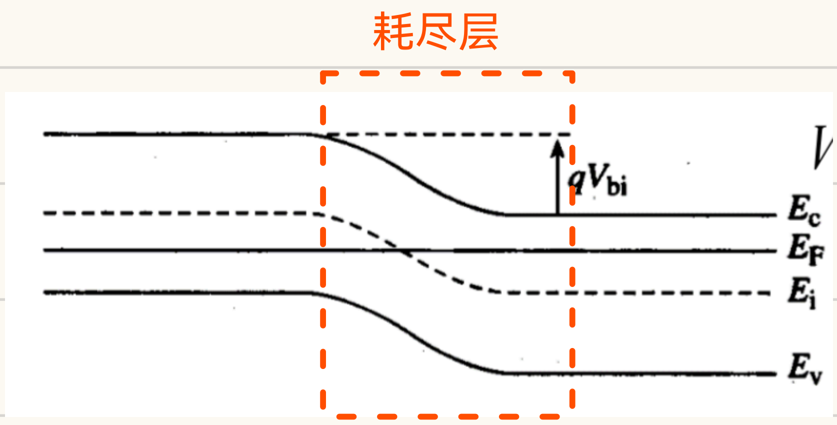
解得电场强度： $E = -\frac{kT}{q}\frac{1}{n}\cdot\frac{dn}{dx}$

积分得电势差： $V_{bi} = \int_{x_N}^{-x_p} E\,dx = \int_{n(-x_p)}^{n(x_N)} \frac{kT}{q}\cdot\frac{1}{n}\,dn = \frac{kT}{q}\ln\frac{n(x_N)}{n(-x_p)}$

边界条件： $n(x_N) = N_D$ 　 $n(-x_p) = n_i^2/p(-x_p) = \frac{n_i^2}{N_A}$ 　——对于非简并掺杂半导体

得电势差： $V_{bi} = \frac{kT}{q}\ln\frac{N_D N_A}{n_i^2}$

推导方法2.



电势能定义: $V_{bi} = V(x_n) - V(-x_p)$

$$= -\frac{1}{q}E_c(x_n) - \left(-\frac{1}{q}E_c(-x_p)\right)$$

$$= \frac{1}{q}\left[E_c(-x_p) - E_c(x_n)\right]$$

本征费米能级弯折与能带相同: $V_{bi} = \frac{1}{q}\left[E_i(-x_p) - E_i(x_N)\right]$

费米能级恒定: $V_{bi} = \frac{1}{q}\left[(E_i - E_F)_{p\text{-side}} + (E_F - E_i)_{n\text{-side}}\right]$

费米能级与载流子浓度的关系:

$$(E_i - E_F)_{p\text{-side}} = kT\ln\frac{p}{n_i}\bigg|_{p\text{-side}} = kT\ln\frac{N_A}{n_i}$$

$$(E_F - E_i)_{n\text{-side}} = kT\ln\frac{n}{n_i}\bigg|_{n\text{-side}} = kT\ln\frac{N_D}{n_i}$$

代换: $V_{bi} = \frac{kT}{q}\ln\frac{N_D N_A}{n_i^2}$

当一侧(例如p-side)是重掺杂时，有: $V_{bi} = \frac{E_g}{2q} + \frac{kT}{q}\ln\frac{N_D}{n_i}$

两种方法的内在联系——爱因斯坦关系式推导过程分析

$$\begin{cases} J_n = qn\mu_n\mathcal{E} + qD_n\dfrac{dn}{dx} = 0 \\ J_p = qp\mu_p\mathcal{E} - qD_p\dfrac{dp}{dx} = 0 \end{cases} \xrightarrow[\varepsilon = \frac{kT}{q}\frac{1}{p}\frac{dp}{dx}]{\text{方法1.}\quad \varepsilon = -\frac{kT}{q}\frac{1}{n}\frac{dn}{dx}} \boxed{\begin{cases} \dfrac{kT}{q} = \dfrac{D_n}{\mu_n} \\ \dfrac{kT}{q} = \dfrac{D_p}{\mu_p} \end{cases}}$$

$\varepsilon = -\frac{kT}{q}\frac{1}{n}\frac{dn}{dx}$ 何来?

$$E = \frac{1}{q}\frac{dE_c}{dx}$$

$$n = N_c e^{-(E_c - E_F)/kT}$$

$$\longrightarrow \frac{dn}{dx} = -\frac{N_c}{kT}e^{-(E_c - E_F)/kT} \cdot \frac{dE_c}{dx}$$

$$\longrightarrow \frac{dn}{dx} = -\frac{n}{kT}\frac{dE_c}{dx}$$

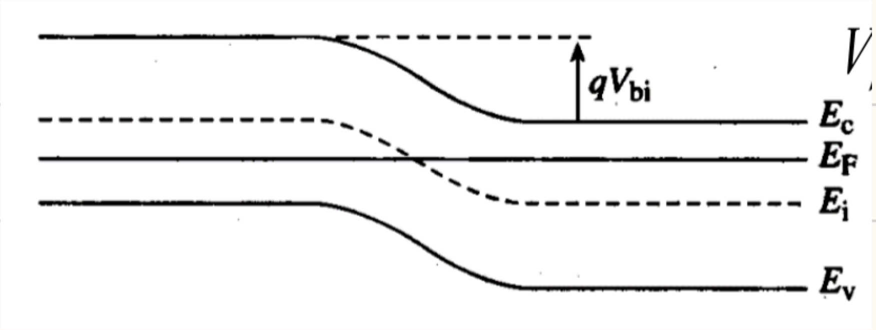
$$\longrightarrow \frac{dn}{dx} = -\frac{n}{kT}q\varepsilon$$

$$\longrightarrow \varepsilon = -\frac{1}{q}\cdot\frac{kT}{n}\cdot\frac{dn}{dx}$$

可见，方法1中使用的爱因斯坦关系式，由借助电场与导带的微分关系推出，这一关系直接在方法2.中被应用

Tips: 以上考虑的都是轻掺杂，在轻掺杂情况下：

(1) 内建电势差必然小于带隙与元电荷之商(Eg/q)



Justification:

$$V_{bi} = \frac{1}{q}[(E_i - E_F)_p + (E_F - E_i)_n]$$

$E_F > E_v(p)$ $E_F < E_c(n)$

So: $V_{bi} < \frac{1}{q}[\frac{1}{2}E_g + \frac{1}{2}E_g] = \frac{E_g}{q}$

Vbi(Si) < 1.12 V, Vbi(Ge) < 0.66 V, Vbi(GaAs) < 1.42 V.

(2) For Si at 300K, if NA=ND=10^15/cm^-3, Vbi=0.6 V.

内建电场场强与宽度

泊松方程

电场高斯定理—积分形式：$\oiint_{\partial V} \vec{E}\cdot d\vec{s} = \frac{1}{\varepsilon}\iiint_V \rho\, dV = \frac{1}{K_s\varepsilon_0}\iiint_V \rho\, dV$

其中：Ks为相对介电常数，ε0为真空介电常数

电场高斯定理—微分形式：$\nabla\cdot E = \frac{\rho}{K_s\varepsilon_0}$

电场—电势微分关系：$E = -\nabla V$

泊松方程：$\nabla^2 V = -\frac{\rho}{K_s\varepsilon_0}$

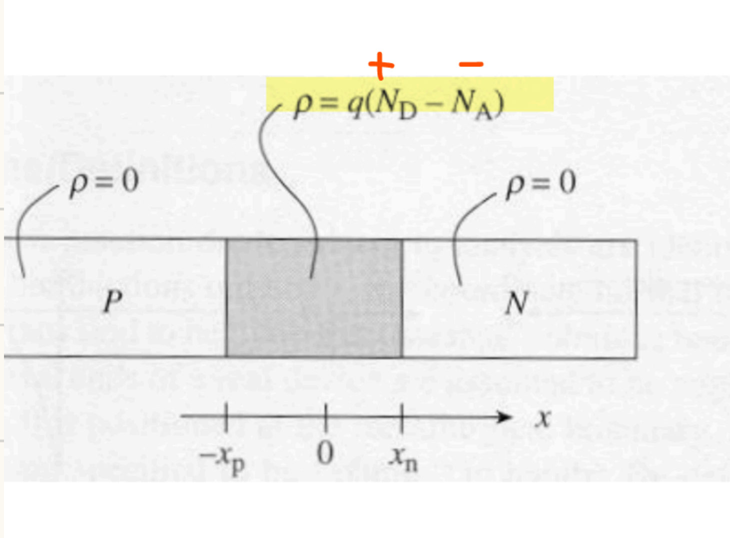
ε0: free space permittivity = 8.85 × 10–14 F/cm

Ks: dielectric constant = 11.9 for silicon, 3.9 for SiO2

ρ: charge density (C/cm3)

耗尽近似

Depletion Approximation states that approximately no free carriers exist in the space charge region and no net charge exists outside of the depletion region (know as the quasi-neutral region)

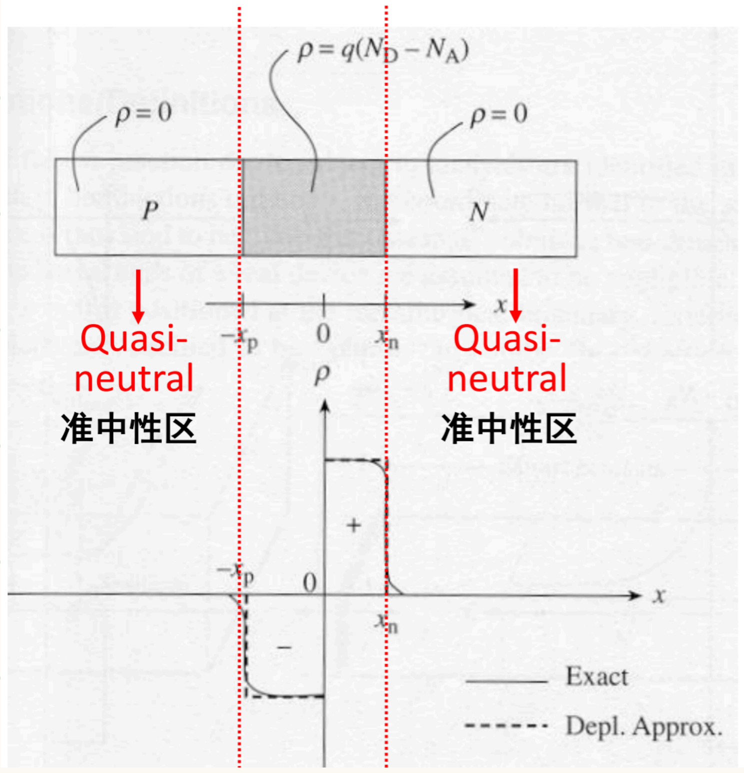


耗尽近似表明，空间电荷区中几乎不存在自由载流子，耗尽区外(准中性区)也不存在净电荷。

突变结的内建电场场强与宽度

高斯定理微分形式一维形式:

$$\frac{dE}{dx}=\frac{\rho}{K_s\varepsilon_0}$$



考虑准中性区:

$$\rho=\begin{cases}N_D+p-n=0\\ N_A+n-p=0\end{cases}$$

故 $\frac{dE}{dx}=0 \longrightarrow E=C$（常数）且 $E=0$

考虑Depletion region p-side

$$\frac{dE}{dx}=\frac{-qN_A}{K_s\varepsilon_0}\longrightarrow E=-\frac{qN_A}{K_s\varepsilon_0}x+C\longrightarrow -\frac{qN_A}{K_s\varepsilon_0}(x+x_p)$$

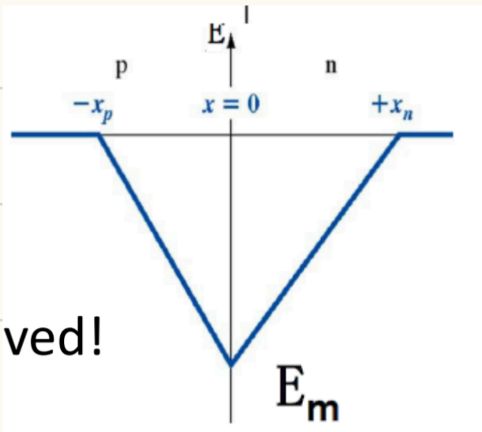
边界(准中性区)条件：电场与连续

考虑Depletion region n-side

$$\frac{dE}{dx}=\frac{qN_D}{K_s\varepsilon_0}\longrightarrow E=\frac{qN_D}{K_s\varepsilon_0}x+C\longrightarrow\frac{qN_D}{K_s\varepsilon_0}(x-x_N)$$

So:

$$E=\begin{cases}-\frac{qN_A}{K_s\varepsilon_0}(x+x_p) & -x_p\le x<0\\ \frac{qN_D}{K_s\varepsilon_0}(x-x_N) & 0\le x\le x_N\\ 0 & \text{else}\end{cases}$$



还有一个边界条件在上述推导过程中我们并未使用，即耗尽层内部的电场必然也是连续的，即:

$$E(0-)=E(0+)=E_m\longrightarrow N_A x_p=N_D x_D \quad ①$$

此时，我们便得到了关于耗尽层宽度的一个方程，只需要再有的一个关于xP和xN的方程，即可求出耗尽层宽度

从哪里获得这个方程呢?
在上述推导过程中，我们仅使用了基本电磁学中，场强与电势、电荷密度的关系，以及稍微一点点有关PN结的知识(准中性区载流子浓度等于掺杂浓度)，并未充分利用PN结的信息。
那有关PN结的哪个信息能够完全反映其内建电场特性呢?
—能带模型!

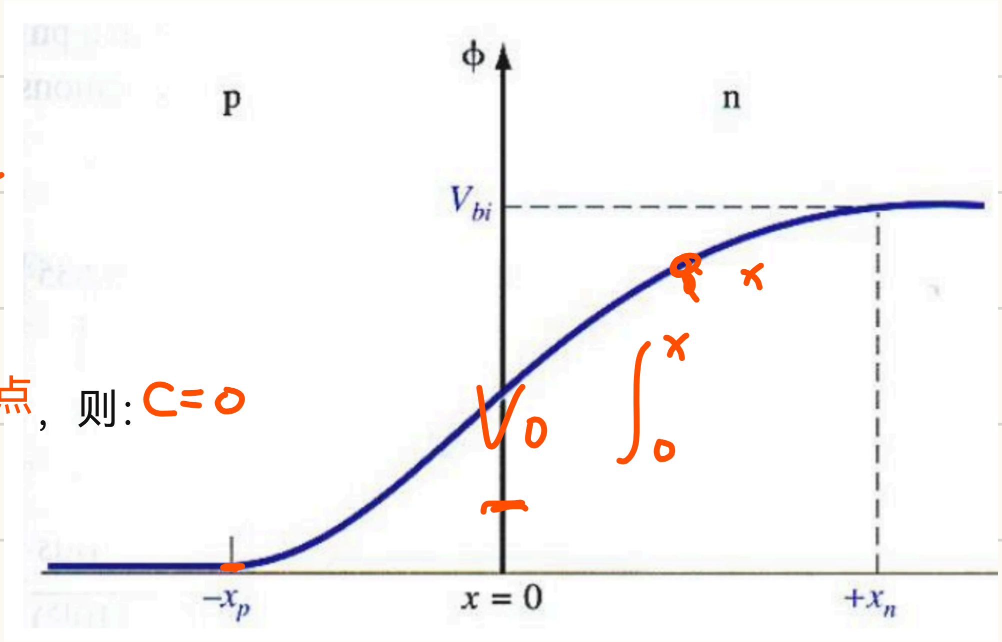
在“内建电势Vbi”一节中，我们利用PN结的能带模型推导出了内建电势差Vbi，所以，这里我们可以利用Vbi这个已知信息，导出有关xP和xN的另一个方程。

考虑耗尽层P端:

$$E = -\frac{qN_A}{K_s\varepsilon_0}(x+x_p)$$

$$\longrightarrow \Delta V = -\int_{-x_p}^{x} -\frac{qN_A}{K_s\varepsilon_0}(l+x_p)\,dl$$

$$\longrightarrow \Delta V = \frac{qN_A}{2K_s\varepsilon_0}(x+x_p)^2 + C$$



考虑边界条件：我们规定准中性区P区为零电势点，则: $C=0$

$$V(x) = \Delta V = \frac{qN_A}{2K_s\varepsilon_0}(x+x_p)^2$$

考虑耗尽层N端:

$$E = \frac{qN_D}{K_s\varepsilon_0}(x-x_N)$$

$$\Delta V = -\int_0^x \frac{qN_D}{K_s\varepsilon_0}(l-x_N)\,dl = \frac{qN_D}{2K_s\varepsilon_0}x_N^2 - \frac{qN_D}{2K_s\varepsilon_0}(x-x_N)^2$$

考虑第二个边界条件：空间电荷区连续，内建电场连续，电场强度和电势也连续

故：x>0时：

$$V(x) = V(0) + \Delta V = V(0-) + \Delta V = \frac{qN_A}{2K_s\varepsilon_0}x_p^2 + \frac{qN_D}{2K_s\varepsilon_0}x_N^2 - \frac{qN_D}{2K_s\varepsilon_0}(x-x_N)^2$$

考虑第三个边界条件：空间电荷区N端点与准中性区N区电势连续

故：x>0时：

$$V(x)\Big|_{x=x_N} = V(-x_p) + V_{bi} = 0 + V_{bi} = V_{bi}$$

即:

$$V_{bi} = \frac{qN_A x_p^2}{2K_s\varepsilon_0} + \frac{qN_D x_N^2}{2K_s\varepsilon_0} \quad ②$$

这便是有关PN结耗尽层宽度的另一个一个方程。

联立①②，我们可以解得:

$$x_n = \sqrt{\frac{2K_s\varepsilon_0 V_{bi}}{q}\frac{N_A}{N_D(N_A+N_D)}}$$

$$x_p = \sqrt{\frac{2K_s\varepsilon_0 V_{bi}}{q}\frac{N_D}{N_A(N_A+N_D)}}$$

$$W = x_n + x_p = \sqrt{\frac{2K_s\varepsilon_0 V_{bi}}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)}$$

总结：内建电场

内建电势 $$V_{bi} = \frac{kT}{q}\ln\frac{N_D N_A}{n_i^2}$$

电场强度
$$E = \begin{cases} -\frac{qN_A}{k_s\varepsilon_0}(x+x_p) & -x_p \le x < 0 \\ \frac{qN_D}{k_s\varepsilon_0}(x-x_N) & 0 \le x \le x_N \\ 0 & \text{else} \end{cases}$$

宽度
$$x_n = \sqrt{\frac{2k_s\varepsilon_0 V_{bi}}{q}\frac{N_A}{N_D(N_A+N_D)}}$$
$$x_p = \sqrt{\frac{2k_s\varepsilon_0 V_{bi}}{q}\frac{N_D}{N_A(N_A+N_D)}}$$
$$W = x_n + x_p = \sqrt{\frac{2k_s\varepsilon_0 V_{bi}}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)}$$

电势
$$V(x) = \begin{cases} 0 & (-\infty, -x_p) \\ \frac{qN_A}{2k_s\varepsilon_0}(x+x_p)^2 & (-x_p, 0) \\ V_{bi} - \frac{qN_D}{2k_s\varepsilon_0}(x-x_N)^2 & (0, x_N) \\ V_{bi} & (x_N, +\infty) \end{cases}$$

两个重要关系
$$N_A x_p = N_D x_D \quad ①$$
$$V_{bi} = \frac{qN_A x_p^2}{2k_s\varepsilon_0} + \frac{qN_D x_N^2}{2k_s\varepsilon_0} \quad ②$$

单边突变结

p+n junction $N_A >> N_D$

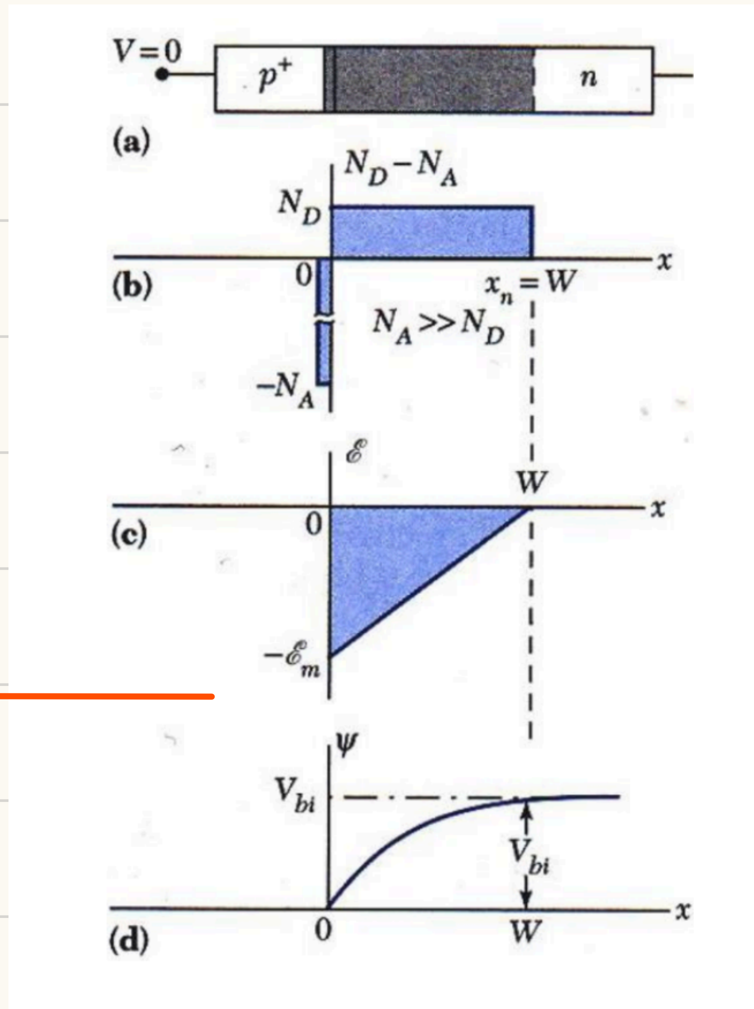
① $N_A x_p = N_D x_N \longrightarrow x_p = \frac{N_D x_N}{N_A} \approx 0$

$W = x_p + x_N \approx x_N$

② $\frac{1}{N_A} + \frac{1}{N_D} \approx \frac{1}{N_D}$

$W \approx \sqrt{\frac{2k_s\varepsilon_0 V_{bi}}{qN_D}}$

$x_N \approx \sqrt{2k_s\varepsilon_0 V_{bi}/qN_D}$



③ $E(x) \approx \frac{qN_D}{k_s\varepsilon_0}(x-W)$ 轻掺杂一侧

$V(x) \approx \frac{V_{bi}}{W}\left(2x - \frac{x^2}{W}\right)$ 轻掺杂一侧

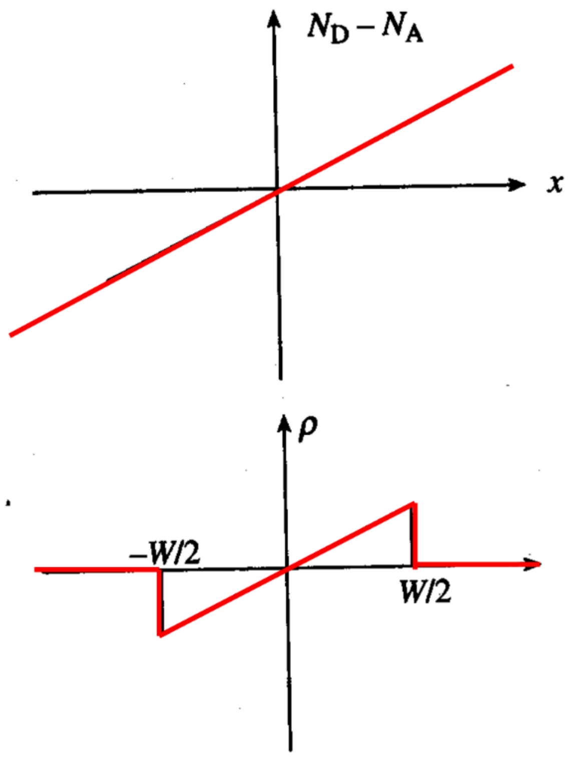
④ $E(0)$ $V(0)$

$E(0) = \frac{2V_{bi}}{W} \approx \sqrt{\frac{2qN_D V_{bi}}{k_s\varepsilon_0}}$

$V(0) = V_{bi} - \frac{qN_D}{2k_s\varepsilon_0}(x-x_N)^2 \Big|_{x=0} = \frac{N_D}{N_A+N_D}V_{bi}$ pn结合单边突变结都适用

Most of V is dropped across the more lightly doped side.

线性缓变结



$$N_D - N_A = ax$$

$$\rho(x) = \begin{cases} qax \ldots -W/2 \le x \le W/2 \\ 0 \ldots\ldots x \le -W/2,\ x \ge W/2 \end{cases}$$

电场强度

$$\nabla \cdot E = \frac{1}{k_s\varepsilon_0}\rho(x)$$

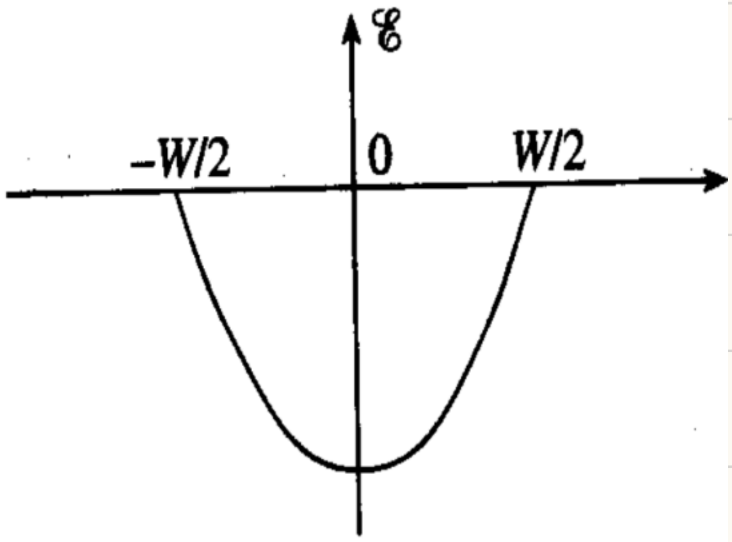
$$\frac{dE}{dx} = \frac{1}{k_s\varepsilon_0}\rho(x)$$

$$E(x) = \frac{qa}{2k_s\varepsilon_0}x^2 + C$$

由 $E(\frac{W}{2}) = E(-\frac{W}{2}) = 0$：

$$C = -\frac{qa}{2k_s\varepsilon_0}\cdot\left(\frac{W}{2}\right)^2$$

故： $E(x) = \frac{qa}{2k_s\varepsilon_0}\left[x^2 - \left(\frac{W}{2}\right)^2\right]$



电势

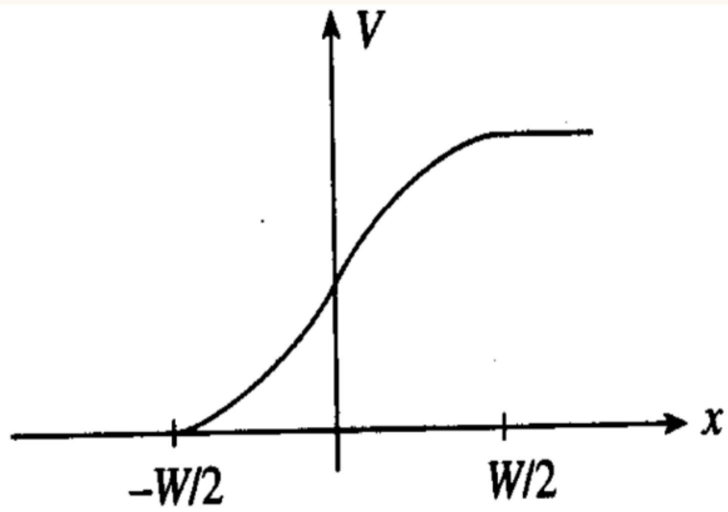
$$E = -\nabla V \longrightarrow V(x) = -\int_0^x E(l)\,dl$$

$$\Delta V = -\int_{-\frac{W}{2}}^{x} \frac{qa}{2k_s\varepsilon_0}\left[l^2 - \frac{W^2}{4}\right]dl$$

$$= -\frac{qa}{6k_s\varepsilon_0}l^3 + \frac{qa}{2k_s\varepsilon_0}\left(\frac{W}{2}\right)^2 l \,\Big|_{-\frac{W}{2}}^{x}$$

$$= -\frac{qa}{6k_s\varepsilon_0}x^3 + \frac{qa}{2k_s\varepsilon_0}\left(\frac{W}{2}\right)^2 x + \frac{qa}{3k_s\varepsilon_0}\left(\frac{W}{2}\right)^3$$

$$V(-\tfrac{W}{2}) = 0 \longrightarrow V(x) = \frac{qa}{6k_s\varepsilon_0}\left[-x^3 + 3\left(\frac{W}{2}\right)^2 x + 2\left(\frac{W}{2}\right)^3\right]$$



当我们知道内建电势差为Vbi时:

$$V\left(\frac{W}{2}\right)=V_{bi} \longrightarrow \frac{qa}{6k_s\varepsilon_0}\left(\frac{W}{2}\right)^3\left[-1+3+2\right]=\frac{qa}{12k_s\varepsilon_0}W^3=V_{bi}$$

$$\longrightarrow W=\left(\frac{12k_s\varepsilon_0 V_{bi}}{qa}\right)^{\frac{1}{3}}$$

内建电势差

$$N_A=N_D=ax\Big|_{x=\frac{W}{2}}=\frac{Wa}{2}$$

$$V_{bi}=\frac{kT}{q}\ln\frac{n(x_N)}{n(-x_P)}=\frac{kT}{q}\ln\frac{(Wa)^2}{(2n_i)^2}$$

$$=\frac{2kT}{q}\ln\frac{Wa}{2n_i}$$

☆ $n(x_N)=N_D$ $n(-x_p)=N_A$ 对线性缓变结不适用