# Lecture 14

# The pn Junction Diode (I)

## I-V Characteristics

## Outline

- pn junction under bias
- IV characteristics

**Reading Assignment:**

Howe and Sodini; Chapter 6, Sections 6.1-6.3

# What shall we learn today?

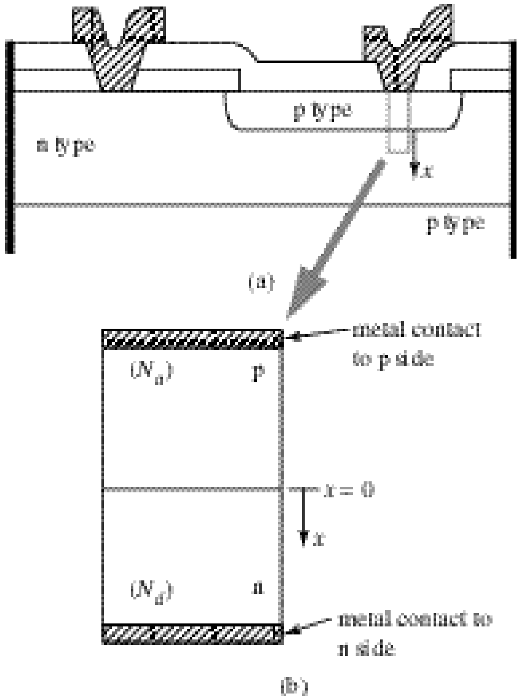
## Summary of Key Concepts

- Application of voltage to pn junction results in disruption of balance between drift and diffusion in SCR
  - In forward bias, minority carriers are ***injected*** into quasi-neutral regions
  - In reverse bias, minority carriers are ***extracted*** from the quasi-neutral regions
- In forward bias, injected minority carriers recombine at the surface (contacts).
- In reverse bias, extracted minority carriers are generated at the surface (contacts).
- Computation of boundary conditions across SCR exploits ***quasi-equilibrium***: balance between diffusion and drift in SCR disturbed very little
- IV characteristics of p-n diode:

$$I = I_o \exp\left[\frac{qV}{kT} - 1\right]$$

# 1. PN junction under bias

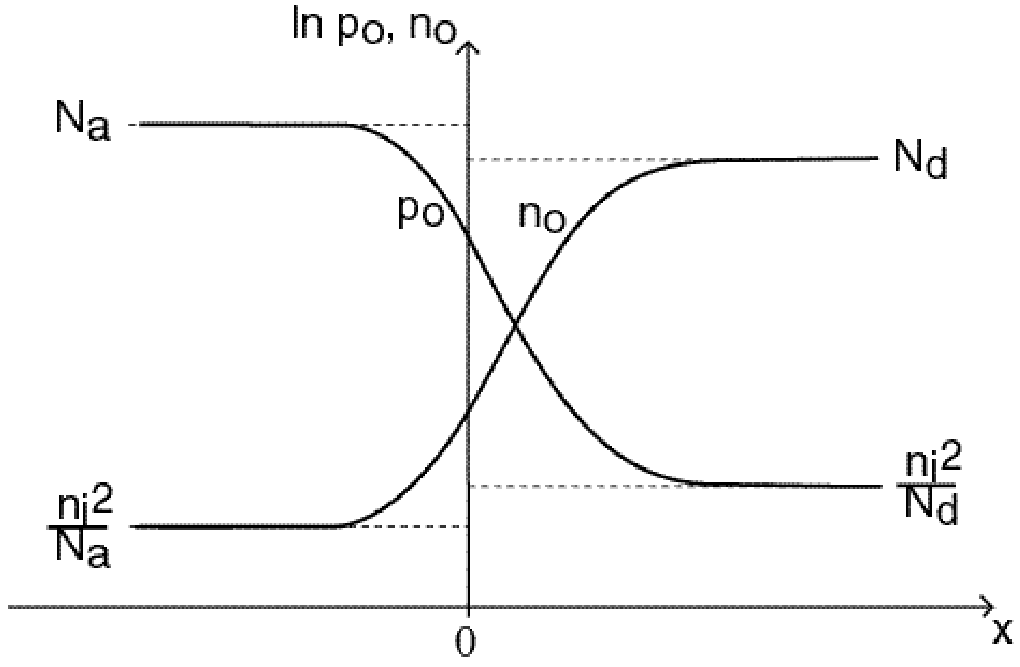
Focus on intrinsic region:

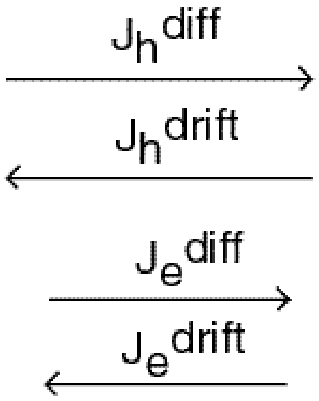


Upon application of voltage:

- Electrostatics upset:
  - depletion region widens or shrinks
- Current flows
  - With rectifying behavior
- Carrier charge storage

# Carrier Profiles: in thermal equilibrium



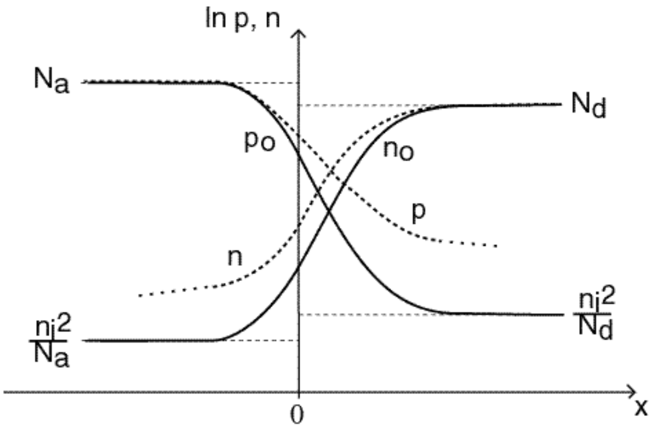


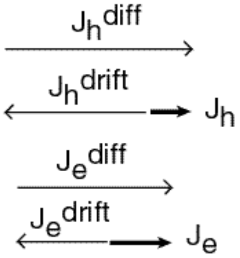
In equilibrium: dynamic balance between drift and diffusion for electrons and holes inside SCR.

$$|J_{drift}| = |J_{diff}|$$

# Carrier Profiles: under forward bias

For V>0, $\varphi_B - V \downarrow$ $|E_{SCR}| \downarrow$ $|J_{drift}| \downarrow$





Current balance in SCR broken:

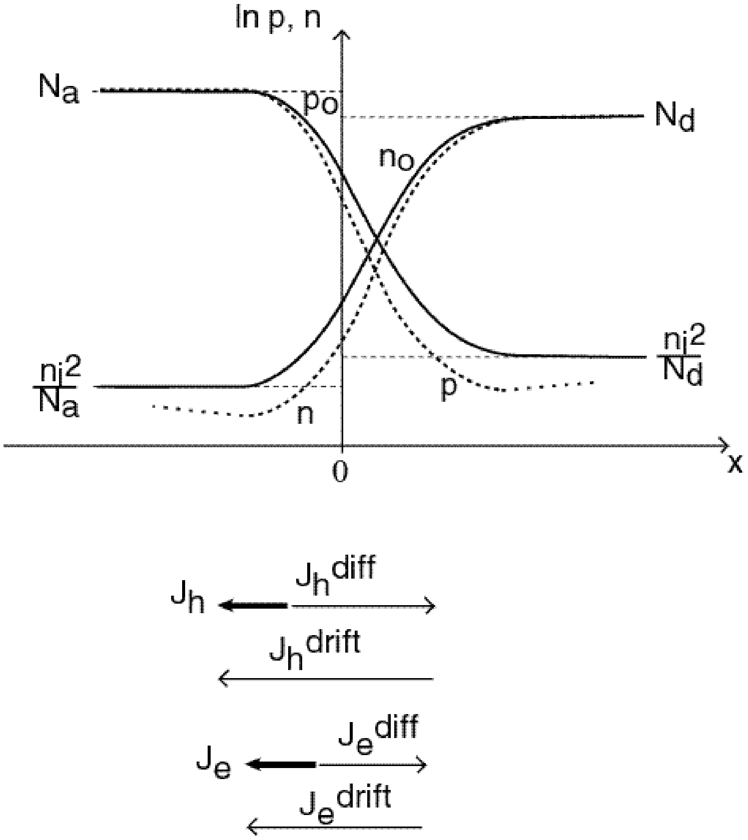
$$|J_{drift}| < |J_{diff}|$$

Net diffusion current in SCR minority carrier *injection* into QNRs.

Carrier flow can be high because lots of minority carriers are in QNRs.

# Carrier Profiles: under reverse bias

For V<0, $\varphi_B - V$ ↑  $|E_{SCR}|$ ↑  $|J_{drift}|$ ↑



Current balance in SCR broken:

$$|J_{drift}| > |J_{diff}|$$

Net drift current in SCR  minority carrier ***extraction*** from QNRs.

Carrier flow is small because there are few minority carriers in QNRs.

# Minority Carrier Concentrations: in QNR

What happens if minority carrier concentrations in QNR changed from equilibrium?

Balance between generation and recombination is broken

- **In thermal equilibrium:** rate of break-up of Si-Si bonds balanced by rate of formation of bonds

$$\text{Si-Si bond} \underset{\text{recombination}}{\overset{\text{generation}}{\rightleftharpoons}} n_o + p_o$$

- **If minority carrier injection:** carrier concentration above equilibrium and recombination prevails

$$\text{Si-Si bond} \xleftarrow[\text{recombination}]{} n + p$$

- **If minority carrier extraction:** carrier concentrations below equilibrium and generation prevails

$$\text{Si-Si bond} \xrightarrow{\text{generation}} n + p$$

# Where does generation and recombination take place?

1. Semiconductor bulk
2. Semiconductor surfaces & contacts

In modern silicon pn-junction devices, surface & contact recombination dominates because:

- Prefect crystalline periodicity broken at the surface
  - lots of generation and recombination centers;
- Modern devices are small
  - high surface area to volume ratio.

***Surfaces and contacts*** are very active generation and recombination centers

***at contacts***, carrier concentrations cannot deviate from equilibrium:

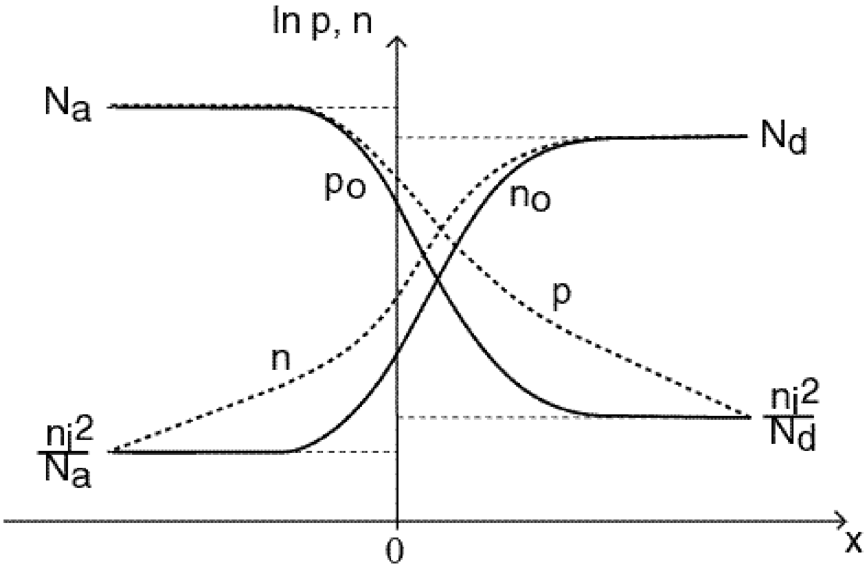
$$n(s) = n_o \; ; \qquad p(s) = p_o$$

In general, it is assumed that at contacts, the rate at which recombination takes place is ***infinite***.

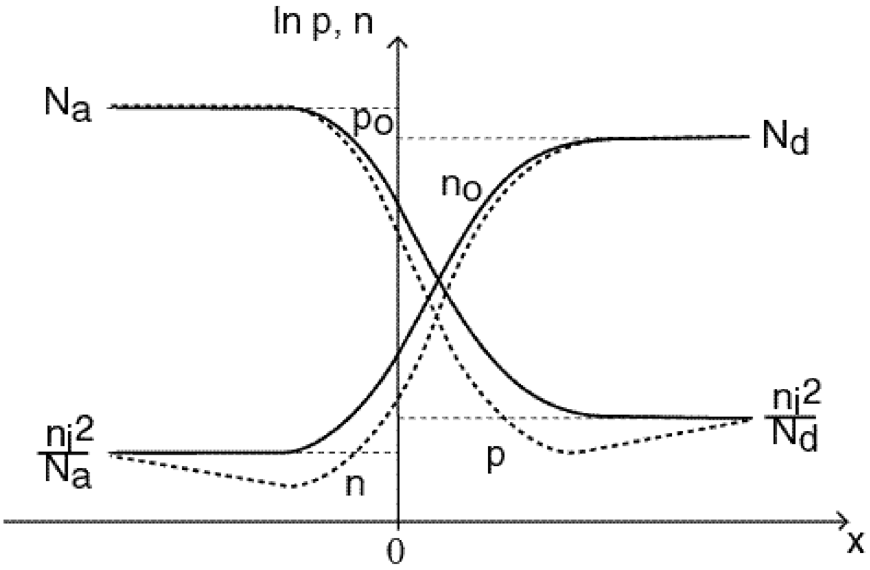
On surfaces, the rate at which recombination takes place is ***finite***.

## Complete physical picture for pn diode under bias:

- **In forward bias,** injected minority carriers diffuse through QNR and recombine at semiconductor surface.



- **In reverse bias,** minority carriers generated at the semiconductor surface, diffuse through the QNR, and extracted by SCR.



## What is the barrier (Bottleneck) to current flow?

- Not generation or recombination at surfaces,
- Not injection or extraction through SCR
- But minority carrier ***diffusion*** through the QNRs

## Development of analytical current model:

1. Calculate concentration of minority carriers at edges of SCR;

2. Calculate minority carrier diffusion current in each QNR;

3. Sum electron and hole diffusion currents.

# 2. I-V Characteristics

**STEP 1:** computation of minority carrier boundary conditions at the edges of the SCR

**In thermal equilibrium in SCR**, $|J_{drift}| = |J_{diff}|$, and

$$\frac{n_o(x_1)}{n_o(x_2)} = \exp\left[\frac{q[\varphi(x_1) - \varphi(x_2)]}{kT}\right]$$

and

$$\frac{p_o(x_1)}{p_o(x_2)} = \exp\left[\frac{-q[\varphi(x_1) - \varphi(x_2)]}{kT}\right]$$

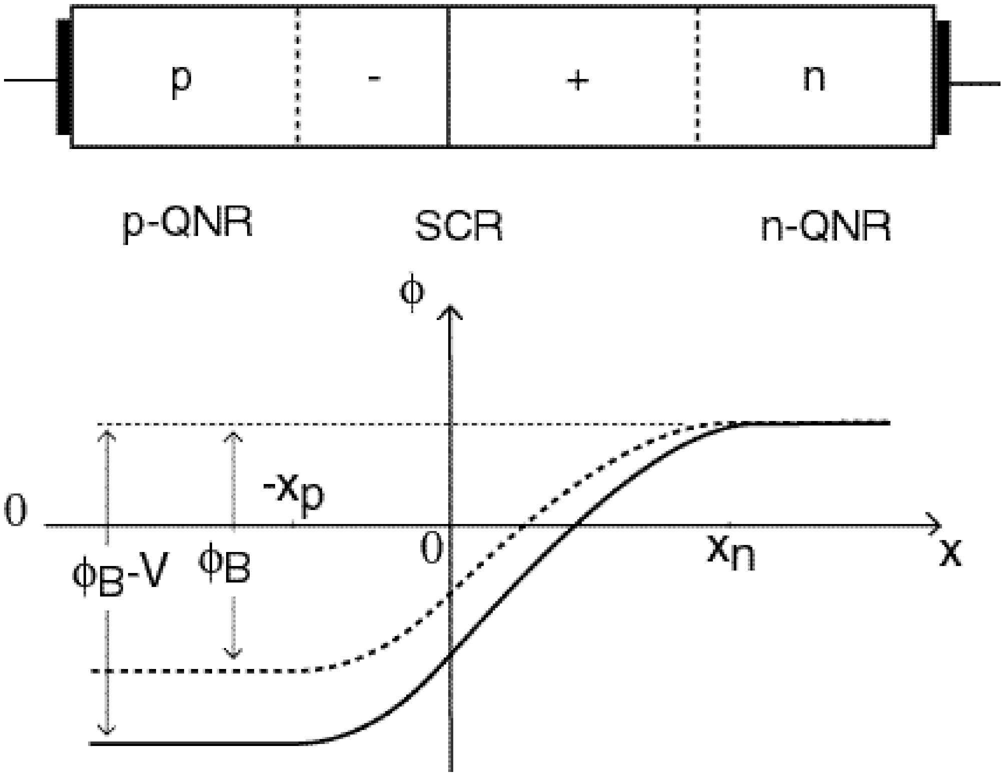
**Under bias in SCR**, $|J_{drift}| \neq |J_{diff}|$, but if difference is small with respect to absolute values of current:

$$\frac{n(x_1)}{n(x_2)} \approx \exp\left[\frac{q[\varphi(x_1) - \varphi(x_2)]}{kT}\right]$$

and

$$\frac{p(x_1)}{p(x_2)} \approx \exp\left[\frac{-q[\varphi(x_1) - \varphi(x_2)]}{kT}\right]$$

This is called ***quasi-equilibrium***.



At edges of SCR, then:

$$\frac{\mathbf{n}(\mathbf{x_n})}{\mathbf{n}(-\mathbf{x_p})} \approx \exp\left[\frac{\mathbf{q}\left[\varphi(\mathbf{x_n}) - \varphi(-\mathbf{x_p})\right]}{\mathbf{kT}}\right] = \exp\left[\frac{\mathbf{q}(\varphi_\mathbf{B} - \mathbf{V})}{\mathbf{kT}}\right]$$

**and**

$$\frac{\mathbf{p}(\mathbf{x_n})}{\mathbf{p}(-\mathbf{x_p})} \approx \exp\left[\frac{-\mathbf{q}\left[\varphi(\mathbf{x_n}) - \varphi(-\mathbf{x_p})\right]}{\mathbf{kT}}\right] = \exp\left[\frac{-\mathbf{q}(\varphi_\mathbf{B} - \mathbf{V})}{\mathbf{kT}}\right]$$

But:

$$p(-x_p) \approx N_a \quad \text{and} \quad n(x_n) \approx N_d$$

This is the ***low-level injection*** approximation: we will discuss this in more detail next time.

Then:

$$n(-x_p) \approx N_d \exp\left[\frac{q(V-\varphi_B)}{kT}\right]$$

and

$$p(x_n) \approx N_a \exp\left[\frac{q(V-\varphi_B)}{kT}\right]$$

Built-in potential:

$$\varphi_B = \frac{kT}{q} \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

Plug in above and get:

$$n(-x_p) \approx \frac{n_i^2}{N_a} \exp\left[\frac{qV}{kT}\right]$$

and

$$p(x_n) \approx \frac{n_i^2}{N_d} \exp\left[\frac{qV}{kT}\right]$$

Voltage dependence:

- **Forward bias (V>0):**

$$n(-x_p) >> n_o(-x_{po})$$
$$p(x_n) >> p_o(x_{no})$$

Lots of carriers available for injection, the higher V, the higher the concentration of injected carriers

forward current can be high.

- **Reverse bias (V<0):**

$$n(-x_p) << n_o(-x_{po})$$
$$p(x_n) << p_o(x_{no})$$

Few carriers available for extraction

reverse current is small.

There is limit to how low minority carrier concentrations drop in reverse bias: **zero!**

Rectification property of the pn diode arises from minority-carrier boundary conditions at edges of SCR.

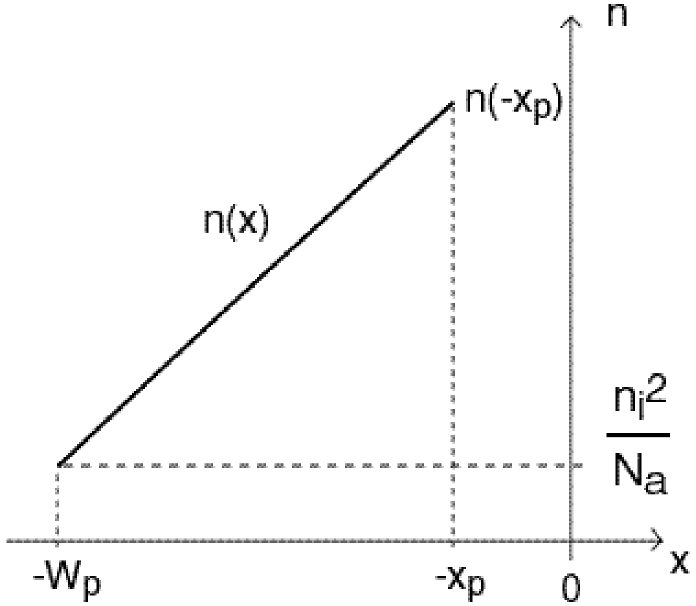
## **STEP 2:** Diffusion current in QNR

Diffusion equation (for electrons in p-QNR):

$$J_n = qD_n \frac{dn}{dx}$$

Inside p-QNR, electrons diffuse to and recombine at the contact

$J_n$ constant in p-QNR      n(x) linear



Boundary conditions:

$$n(x=-W_p) = n_o = \frac{n_i^2}{N_a} \qquad n(-x_p) = \frac{n_i^2}{N_a}\exp\left[\frac{qV}{kT}\right]$$

Electron profile:

$$n_p(x) = n_p(-x_p) + \frac{n_p(-x_p) - n_p(-W_p)}{-x_p + W_p} \cdot \left(x + x_p\right)$$

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Electron diffusion current:

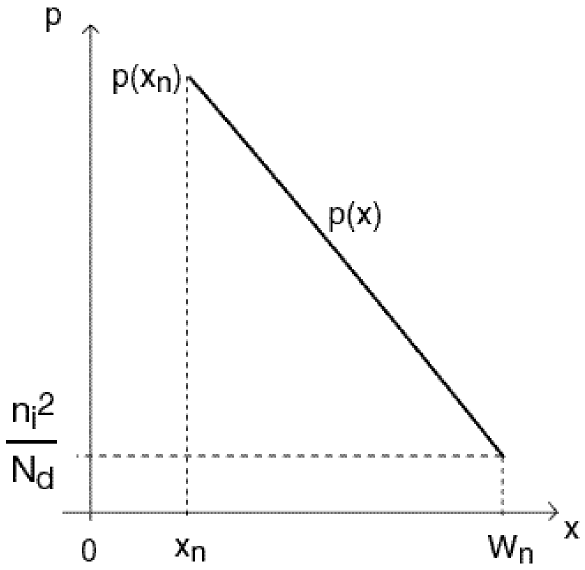
$$J_n = qD_n \frac{dn}{dx} = qD_n \frac{n_p(-x_p) - n_p(-W_p)}{W_p - x_p}$$

$$= qD_n \left[ \frac{\frac{n_i^2}{N_a} \exp\left[\frac{qV}{kT}\right] - \frac{n_i^2}{N_a}}{W_p - x_p} \right]$$

or

$$J_n = q \frac{n_i^2}{N_a} \cdot \frac{D_n}{W_p - x_p} \cdot \left[ \exp\left(\frac{qV}{kT}\right) - 1 \right]$$

Similarly for holes in n-QNR:



$$J_p = q\frac{n_i^2}{N_d}\cdot\frac{D_p}{W_n - x_n}\cdot\left[\exp\left(\frac{qV}{kT}\right) - 1\right]$$

**STEP 3:** sum both currents:

$$J = J_n + J_p = qn_i^2\left(\frac{1}{N_a}\cdot\frac{D_n}{W_p - x_p} + \frac{1}{N_d}\cdot\frac{D_p}{W_n - x_n}\right)\cdot\left[\exp\left(\frac{qV}{kT}\right) - 1\right]$$

Current is:

$$I = qAn_i^2\left(\frac{1}{N_a}\cdot\frac{D_n}{W_p - x_p} + \frac{1}{N_d}\cdot\frac{D_p}{W_n - x_n}\right)\cdot\left[\exp\left(\frac{qV}{kT}\right) - 1\right]$$

Often written as:

$$I = I_o\left[\exp\left(\frac{qV}{kT}\right) - 1\right]$$

[**We shall discuss this result in detail next time**]

# What did we learn today?

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