Silicon Photonics
矽光子學
A Selection of Photonic Devices (A)

課程編號：**941 U0460**
科目名稱：矽光子學
授課教師：黃鼎偉
時間地點：一**678** 明達館 **303**

6.1 OPTICAL PHASE MODULATORS AND VARIABLE OPTICAL ATTENUATORS

OPTICAL PHASE MODULATORS AND VARIABLE OPTICAL ATTENUATORS

- Optical Modulation: a change in the optical field due to some applied signal, typically an electrical signal.
  - The change in the optical field is usually derived from a change in refractive index of the material involved, or via a direct change in intensity of the optical wave.
  - The most efficient means of implementing optical modulation in silicon via an electrical signal is to use carrier injection or depletion.
  - This effect can be used to produce either *variable optical attenuators* (VOAs) or *phase modulators*.

Optical Phase Modulator

- An optical phase modulator is a device that can dynamically vary the phase of an optical wave in a manner determined by some applied driving function.
- Consider an optical phase modulator that operates via injection of free carriers, into the region in which an optical mode is propagating., the injection of carriers is therefore related to the current flowing in the device, which is usually regarded as the driving function

Modeling of Semiconductor Devices

- By solving the equations governing charge behavior in semiconductor devices, principally the continuity equation and Poisson's equation.
- The complex nature of carrier transport and distribution requires a range of models to adequately describe them sufficiently well, and hence care must be taken to ensure that both sufficient detail is included in the supporting models, and that constants are defined sufficiently accurately for the work being undertaken.

Basic Device Geometry, and the Aim of Modeling

- A common consideration is whether operating speed or electrical power consumption is more important.
- Alternatively, minimal optical loss may be the prime consideration.
- Consider a device in which we wish to maximize the DC performance of a phase modulator.
- In practice this means we wish to maximize the refractive index change for a given current.
- Alternatively, considering the charges within the device, this means we would like to have high carrier density only where the optical mode exists, and none elsewhere.

Basic Device Geometry, and the Aim of Modeling

- One of the simplest ways of setting up current flow through the device is to use a *p-n* junction.
- However, since a *p-n* junction requires relatively high doping concentrations in the *p* and *n* regions, such doping will cause high optical loss via absorption if the doped regions are formed in the parts of the waveguide where the optical power is concentrated.
- Consequently a *p-i-n* structure is more appropriate for such a device, the intrinsic region coinciding with the region of the waveguide containing the optical power.

Optical phase modulator *p-i-n* structure

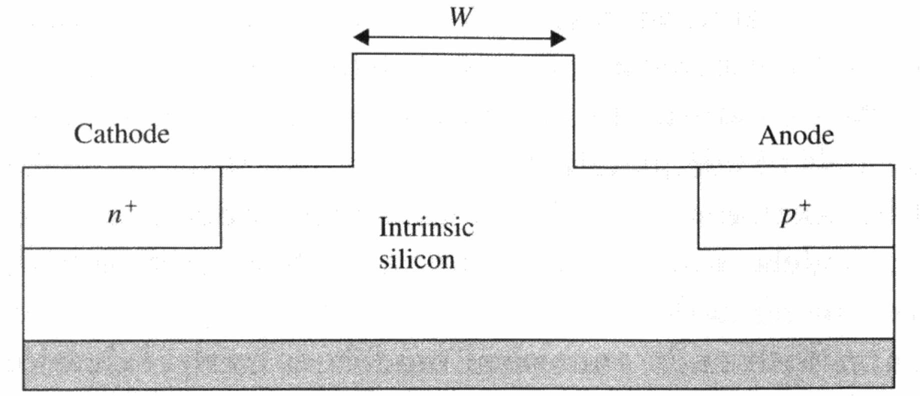

Figure 6.1 Optical phase modulator *p-i-n* structure

Basic Device Geometry, and the Aim of Modeling

- In order to optimize the device for refractive index change, we need to achieve controlled current flow throughout the rib.
- We could obtain better injection densities in the centre of the rib using an alternative *p-i-n* orientation, Figure 6.2.
- Geometrical parameters to be considered:
  - 1 The angle of the rib walls
  - 2 The rib width and height
  - 3 Depth of the *n*+ and *p*+ regions
  - 4 Lateral displacement of *n*+ regions from the base of the rib.

Symmetrical optical phase modulator *p-i-n* structure

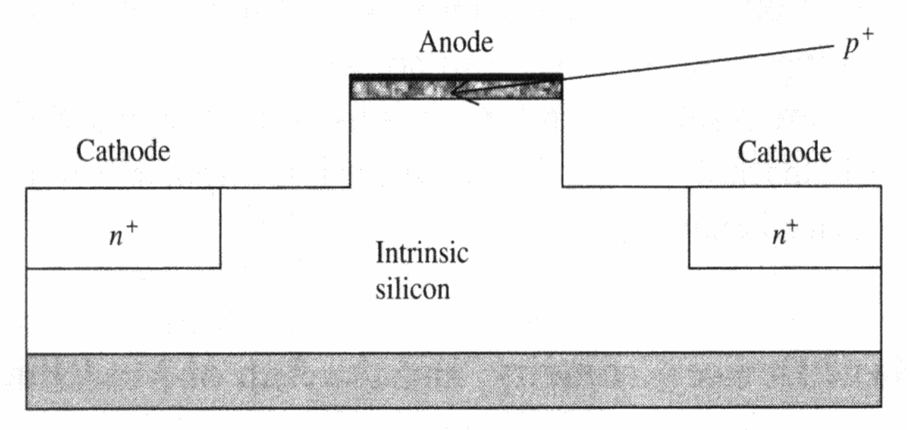

Figure 6.2 Symmetrical optical phase modulator *p-i-n* structure

Generalized three-terminal phase modulator

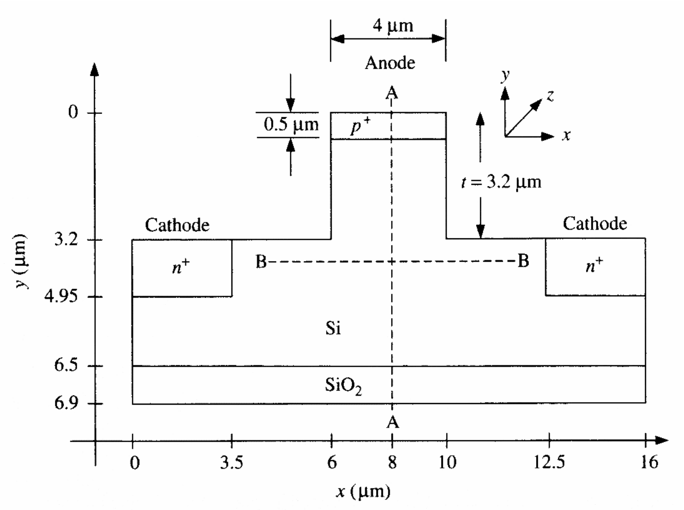

Figure 6.3 Generalized three-terminal phase modulator for performance modeling.

Generalized three-terminal phase modulator

- The device is based upon an SOI wafer with a silicon overlayer of 6.5 μ m.
- In some senses this layer thickness is arbitrary, but the intention is that a large, multi-micron device is to be modeled, such that coupling to or from optical fibers is relatively efficient.
- Notice that the dimensions are such that the single-mode criteria as defined by equation 4.12 are satisfied.
- Consider the device under forward bias (i.e. a positive voltage applied to the p^+ terminal with respect to the n^+ terminals).
- This will cause holes and electrons to be injected into the intrinsic silicon region, constituting a current.

Generalized three-terminal phase modulator

- Since the structure forms a *p-i-n* diode it will have the diode characteristic associated with silicon devices, with a switch-on voltage of approximately 0.6 V.
- Therefore we must forward-bias the device by more than 0.6 V to obtain current flow.
- Consider for example, a forward bias of 0.9 V. The carrier injection concentration will be influenced by the doping concentrations of the p^+ and n^+ regions, which thus far are undefined. Initially let both regions be doped to a density of 5 x 10^{18} cm^{-3}.

Profile of the fundamental mode in an SOI rib waveguide

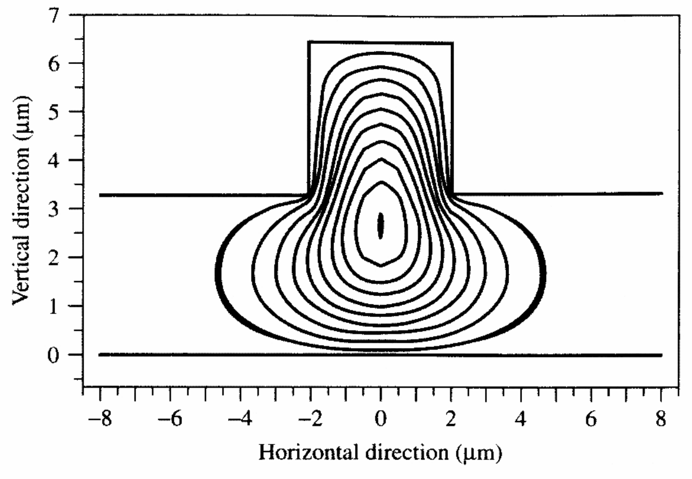

Figure 6.4 Profile of the fundamental mode in an SOI rib waveguide

Generalized three-terminal phase modulator

- It is important to consider the concentration of carriers in the region of the optical mode.
- Clearly to do this we must model the mode profile.
- A typical mode profile is shown in Figure 6.4, with contours of optical intensity in 10 % steps.
- The exact mode profile will vary with changes in the rib geometry, but from Figure 6.4 we can see that even for a relatively shallow rib, almost 80 % of the power is contained under the rib.
- From Figures 6.5 and 6.6, we can see from both figures that the level of injected carriers is of the order of 2 x 10^{17} cm^{-3}, and the variation in injected carrier density across the region of the optical mode is of the order of 2 x 10^{16} cm^{-3}.

Injected carrier density along a vertical section at *x* = 8

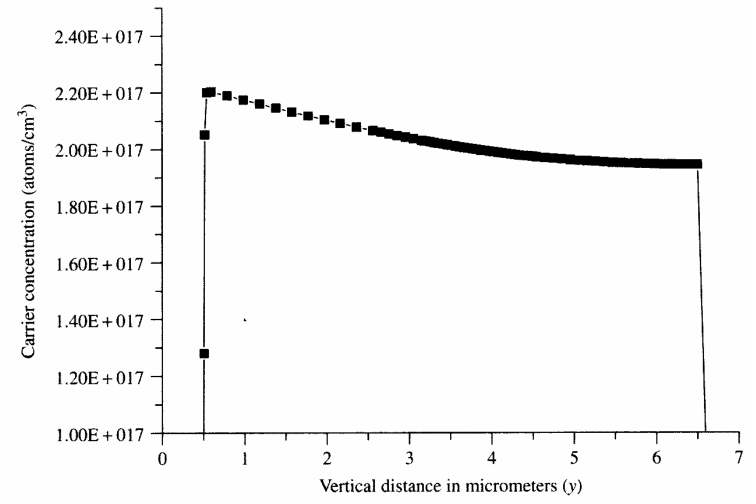

Figure 6.5 Injected carrier density along a vertical section at *x* = 8

Injected carrier density along a horizontal section at y = 3.8

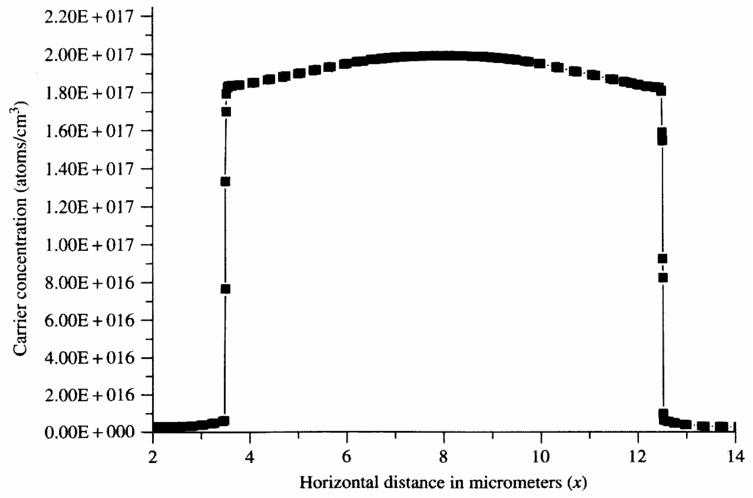

Figure 6.6 Injected carrier density along a horizontal section at y = 3.8

Effect of Parametric Variation on the DC Efficiency of an Optical Modulator

- Consider the effect of the parametric variations
  - 1 The angle of the rib walls
  - 2 The rib height and width
  - 3 Depth of the n^+ and p^+ regions
  - 4 Lateral displacement of *n*+ regions from the base of the rib.

The Angie of the Rib Walls

- To fabricate a device with a rib wall at a specific angle is very difficult.
- Using an anisotropic etch we can achieve an angle of 54.7° to the surface (an exposed (111) plane).
- Consequently, let us compare the injected carriers for a device with vertical walls and one with angled walls (54.7°) shown in Figure 6.7 .
- From Figure 6.8 and Figure 6.9, the modulator with angled walls provides significantly improved carrier injection, as compared to the corresponding injection from the modulator with vertical rib walls.
- It is also worth noting that the uniformity of the carrier density is slightly increased for the angled rib walls.

Three-terminal phase modulator with angled rib walls

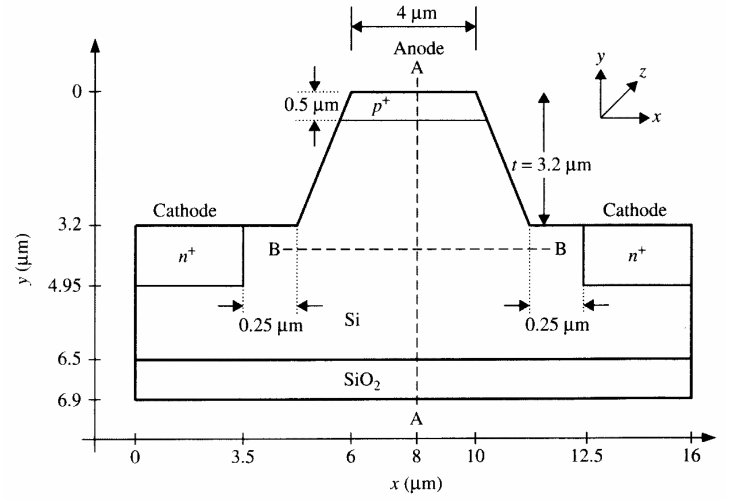

Figure 6.7 Three-terminal phase modulator with angled rib walls.

Comparison of injected carriers along *x* = 8

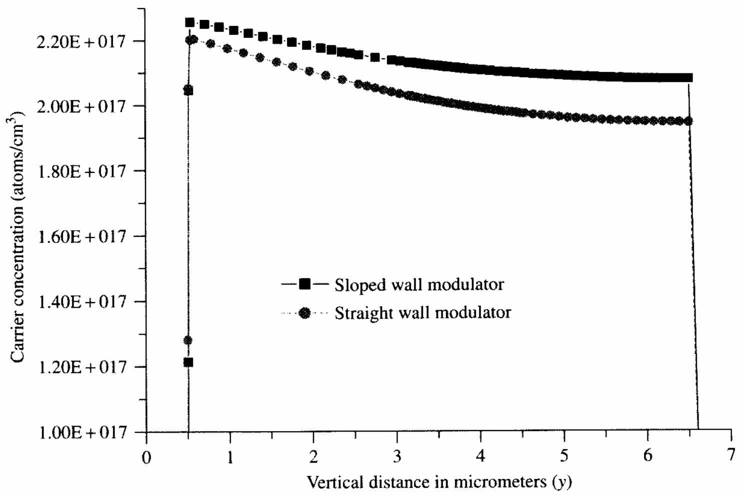

Figure 6.8 Comparison of injected carriers along *x* = 8.

Comparison of injected carriers along *y* = 3.8

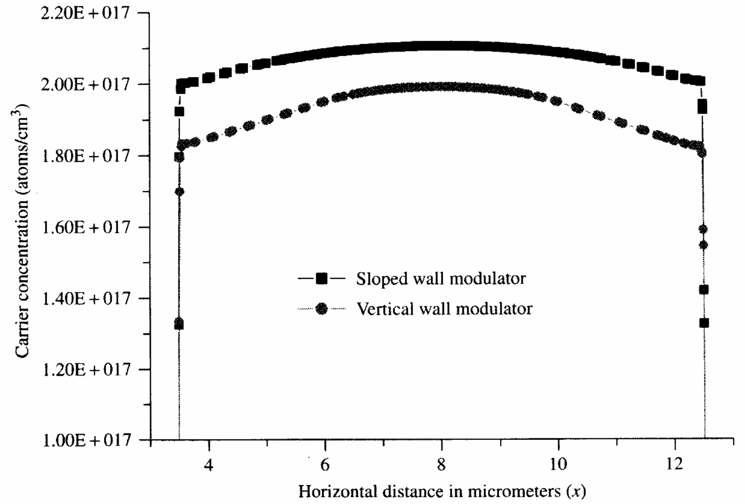

Figure 6.9 Comparison of injected carriers along *y* = 3.8.

The Effect of the Rib Height and Width

- In order to fulfill the single-mode requirements of section 4.4, *t* needs to be less than or equal to 3.25 μm ⇨ *t* = 3.2 μm in Figure 6.7.
- In order to demonstrate the effects let us assume a value of *t* = 2 μm.
- Figure 6.10 shows that the injected carrier density along *x* = 8 is not greatly affected by changes to the rib height, particularly in the most intense part of the optical mode.
- Figure 6.11 shows the variation along *y* = 5.5, the variation is at its largest, it is still less than 1 %

Effect of rib height on injected carriers along *x* = 8

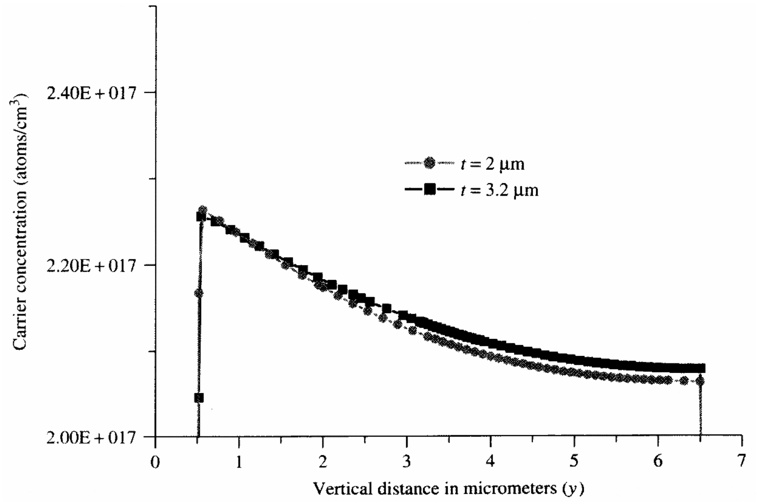

Figure 6.10 Effect of rib height on injected carriers along *x* = 8

Effect of rib height on injected carriers along $y = 5.5$

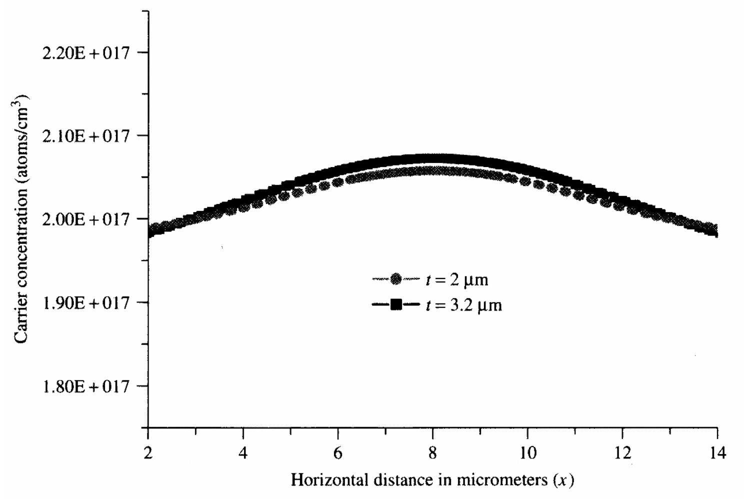

Figure 6.11 Effect of rib height on injected carriers along y = 5.5

The Effect of the Rib Height and Width

- The variation of rib width may be expected to yield more dramatic changes in injected carrier density.
- Since the carrier profiles don't vary significantly with rib width (although of course the current density will change due to the variation in device area), a comparison can be made simply by comparing the peak carrier injection at corresponding points in the devices.
- In order to evaluate the effect of rib width on peak carrier concentration, three variants of the device were modeled, with rib widths of 3 μm, 4 μm and 5 μm.

Effect of rib width on peak carrier concentration

- It is clear that the rib width has little effect on the injected carrier density.
- Therefore, in an application where rib width is important, it could be varied whilst remaining confident of achieving predictable carrier concentrations.

Table 6.1 Effect of rib width on peak carrier concentration.

Rib width (µm)	3	4	5
Peak carrier concentration along $y = 3.2$ ($\times 10^{17}$ cm^{-3})	2.09	2.12	2.06
Peak carrier concentration along $y = 2$ ($\times 10^{17}$ cm^{-3})	2.15	2.17	2.18

Depth of the n^+ and p^+ Regions

- There would be a detrimental effect if the p^+ region were made any deeper since it would encroach onto the region of the optical mode, causing significant absorp-tion ⇨ only the depth of the n^+ regions was varied.
- In order to consider the variation in depth, four depths were considered: 0.5 μm, 1.2 μm, 1.75 μm and 2.5 μm, a significant variation.
- The concentration of the n+ regions was assumed to remain constant at 5 x 10^{18} cm^{-3}.
- The results suggested that there may be some optimum depth, because the 1.2 μm depth produced the highest level of injection, although only marginally higher than the other depths evaluated.

Variation in injected carrier density with contact depth

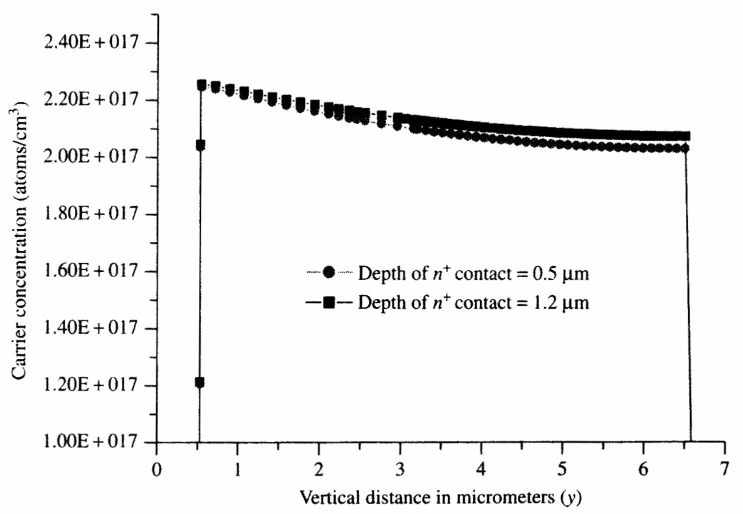

Figure 6.12 Variation in injected carrier density with contact depth.

Depth of the n^+ and p^+ Regions

- An example result is shown in Figure 6.12, which clearly shows little variation between devices with different depth contacts.
- This is particularly interesting because more recent work with different device geometries suggests that a deeper contact significantly improves the device efficiency, particularly if the contact reaches the depth of the buried oxide layer.
- It should also be borne in mind that the deeper the contact, the more likely the optical mode is to impinge on the doped region, resulting in absorption.

Lateral Displacement of n^+ Regions from the Base of the Rib

- The impact of fabrication tolerances may also manifest itself as a translation of the n^+ regions.
- An example result comparing distances from the base of the rib to the n^+ region of 0.25 μm, 1 μm and 4 μm is shown in Figure 6.13
- The level of injected carriers is reduced when the contact spacing is increased. Increasing the spacing from the rib base to the n+ region from 0.25 μm to 1 μm results in a reduction in injected carrier density of approximately 2 % at the centre of the rib, perhaps less than would have been expected.
- However, increasing the spacing to 4 μm reduces the injection efficiency significantly.

Variation in injected carrier density along x = 8 for different n^+ contact positions

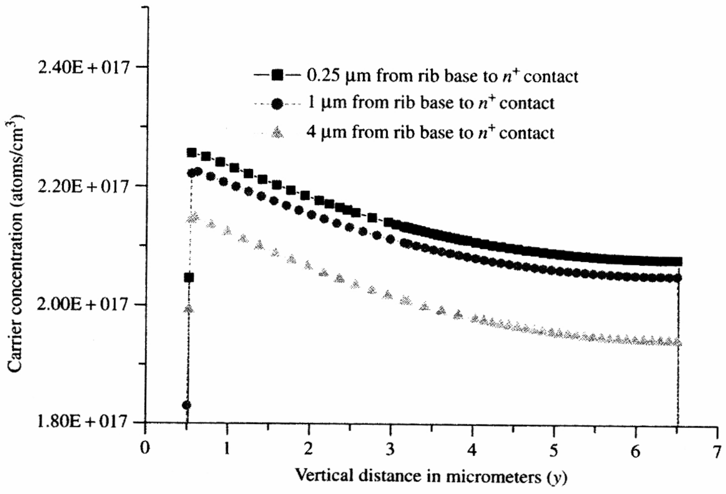

Figure 6.13 Variation in injected carrier density along x = 8 for different n^+ contact positions.