RF applications of PIN diodes

Chin-Leong Lim
RF Applications of PIN diodes

IEEE MTT-ED-SSCS Penang Chapter,
Malaysia.
Tuesday, 24 June, 2008
PIN diode basics

...used by lesser engineers who are confused by anything with >2 legs?
What is the PIN diode?

The PIN diode - is it a current-controlled resistor, as is generally thought?

Sometimes it is, sometimes it is not.
Basic PIN diodes

- **Epitaxial (epi) diode**
  - start with heavily doped substrate
  - grow epi I-layer
  - diffuse the p-type region from the top

- **Bulk diode**
  - start with lightly doped substrate
  - diffuse n-region and p-region from top & bottom
Diode physical characteristics

- **Epi diode**
  - thin I-layer (3 to 20µ)
  - I-region has imperfections in the silicon crystal lattice, leading to short lifetime (5 to 300 nsec.)
  - higher doping density in the I-layer

- **Bulk diode**
  - thick I-layer (25 to 125µ)
  - very pure I-region, producing long lifetimes (300 to 3000 nsec.)
  - low doping density in the I-layer
Diode electrical characteristics

- resistance at a given forward current
- total capacitance at a given reverse voltage
- cutoff frequency, $f_C$
- dielectric relaxation frequency, $f_{DR}$
- distortion performance
PIN diode cutoff frequency

\[ f_c = \frac{1}{2 \pi \tau} \]

\( \tau \) = minority carrier lifetime

\( f \) = operating frequency of the circuit

- Diode acts like a pn junction device
- Diode acts like a current-controlled inductor or capacitor
- Diode acts like a current-controlled resistor

\( \frac{f}{f_c} \)
PIN diode cutoff frequency (continued)

- **Epi diodes**
  - $5\text{ns} < \tau < 50\text{ns}$
  - $32 < 10f_C < 320\text{ MHz}$
  - cannot safely be used as a current controlled resistor below 500 MHz.

- **Bulk diodes**
  - $1000\text{ns} < \tau < 3000\text{ns}$
  - $55 < 10f_C < 160\text{ KHz}$
  - best choice as a current controlled resistor down to 0.5 MHz.

- THESE ARE SWITCH DIODES

- THESE ARE ATTENUATOR DIODES
Diode impedance vs. forward bias at 10 MHz

Bulk diode, \( f_C = 80\text{KHz} \)

Epi diode, \( f_C = 10\text{MHz} \)

Arrow shows change in impedance with increasing forward bias current
Dielectric relaxation frequency

$$f_{DR} = \frac{1}{2 \pi \rho \varepsilon}$$

$$\rho = \text{l-layer bulk resistivity}$$
$$\varepsilon = 10^{-12} \text{ F/cm} = \varepsilon_{\text{o}} \text{ or}$$

if $\rho = 2000$, then $f_{DR} = 80 \text{ MHz}$
if $\rho = 10$, then $f_{DR} = 16 \text{ GHz}$

where $f$ is the circuit operating frequency

- $f < f_{DR}$
- $f > f_{DR}$

Graph showing capacitance vs. reverse voltage with $0.5$ and $1$ units.
Dielectric relaxation frequency (continued)

- **Epi diodes**
  - low resistivity I-layer
  - $f_{DR}$ above 10 GHz
  - needs some reverse voltage to achieve minimum capacitance

- **Bulk diodes**
  - high resistivity I-layer
  - low values of $f_{DR}$
  - need no reverse voltage to achieve minimum capacitance at operating frequency

- THESE ARE LOW CURRENT SWITCH DIODES
- THESE ARE ATTENUATOR OR LOW DISTORTION SWITCH DIODES
Resistance vs. bias current

- **bulk attenuator diode** ($\tau=1500$ nS)
- **epi switching diode** ($\tau=200$ nS)
- **thin bulk diode** ($\tau=500$ nS)
Bulk and epi diodes

- Bulk diodes offer low distortion at all levels of resistance
- Bulk diodes offer low dielectric relaxation frequency
- **Bulk diodes make excellent attenuators**

- epi diodes offer low resistance at low current
- **epi diodes make excellent switches**
My first encounter with a PIN diode - front-end of an automotive FM broadcast-band receiver

Deceptively simple circuit - PIN parasitic capacitance absorbed into parallel resonant tank.

Large attenuation possible because PIN is connected to hi-Z point.
Application: Switch
Linear model of the PIN diode (for $f > f_c$)

- $R_j$ is the current controlled resistance (or reactance if $f < f_c$)
- Parasitics define the limits to switch performance
- Total capacitance = $C_p + C_j$. Capacitance limits performance of series switches
- Package inductance limits performance of shunt switches
Diode parasitics limit performance as frequency increases

- series switch
  - decrease in isolation with frequency due to package & junction capacitance

- shunt switch
  - decrease in isolation with frequency due to package inductance
Switching PIN diodes trade off resistance for capacitance

The diodes with the smallest contacts and thickest epi have the lowest capacitance, but they require higher current to reach a given value of RF resistance.
A model of a PIN diode (SOT-23 package)

- When a diode is used as a series switch, $C_p$ and $C_j$ add. The result is diminished isolation under zero or reverse bias when $R_j$ is very large.

- The only solution in wideband circuits is to use a diode with lower $C_j$. 

\[ C_{\text{package}} = 0.08\text{pF} \]

\[ L = L_{\text{leadframe}} + L_{\text{bondwire}} = 2\text{nH} \]
An extreme case of isolation degraded by PIN capacitance

Series PIN switch in LPCC 2x2 for 10W WCDMA (~2GHz)

Evaluation board isolation at zero bias

Almost no isolation at 3 GHz!
A parallel inductor improves a series diode's isolation

- For narrowband circuits, an inductor can be added in parallel with the diode to resonate the total capacitance at the frequency of interest.

- A large blocking capacitor must be added to avoid shorting out bias current.

Circuit analyzed
The HSMP-3890 (Ct = 0.3pF) is analyzed as a series switch.
The HSMP-3860 (Ct = 0.2pF) is analyzed as a series switch.

![Diode Symbol]

### Graph

**HSMP-3860 PIN diode**
**Calculated performance**

- **Frequency, GHz**
  - 0.5
  - 0.6
  - 0.7
  - 0.8
  - 0.9
  - 1.0
  - 1.1
  - 1.2
  - 1.3

- **Isolation, dB**
  - -50
  - -40
  - -30
  - -20
  - -10
  - 0

**With parallel inductance**

**Without parallel inductance**

155nH
A novel idea for improving isolation in series switch

**Twin-T notch filter**

A transmission zero at $f_c$ when the output of a LPF & a HPF T-networks are combined at 180° phase.

$$f_c = \frac{1}{2\pi RC}$$

RC values shown below ("balanced") gives deepest notch.

![Diagram of Twin-T notch filter](image-url)
Twin T concept applied to anti-series PIN switch

- Series capacitors ($C_{\text{off}}$) in Hi-pass arm formed by OFF PIN diodes.
- $R_{\text{sh}}$ doubles as biasing resistor.
- Lo-pass arm formed by external RC.
- *No inductor!*
Conventional SOT-23 PIN diode
total inductance = 2nH

$L_p = 2nH$

$L_l = 0.5nH$

$L_b = 1nH$
Low inductance package
total inductance is < 1nH

When leads 1 and 2 are connected together, mutual inductance in the bondwires cancels bondwire inductance. Total package inductance in this case is approximately 0.8 nH.
The wrong way in which to mount the shunt switch

- Mounting it as a conventional diode results in a total shunt inductance of 1.1nH (total of diode and via hole inductance)
The correct way to use a shunt switch

- Cut the microstrip line to integrate lead and bondwire inductances into a low pass filter structure.
- Total shunt inductance is 0.8nH
Comparing the performance of the two mounting methods

- When the diode is reverse biased, the correct mounting method forms a low pass filter with lower insertion loss.
- When the diode is forward biased, the lower shunt inductance of the correct method results in higher isolation.
An even better way to use a shunt switch (especially > 2 GHz)

- Use a radial stub to provide RF ground for lead 3, with a high impedance parallel line to ground for DC return.
- Set the length of the stub to be shorter than nominal so that it presents a capacitive reactance to lead 3 ($C_{stub}$), such that it resonates the 0.5nH at the design frequency.

![Diagram showing a radial stub and shunt switch configuration](image)
Improve isolation by PCB layout

Coupling between mounting pads can be reduced somewhat through the use of grounded strips between the four mounting pads.
Improve isolation by PCB layout

Coupling between mounting pads can be reduced somewhat through the use of grounded strips between the four mounting pads.
T/R switch requiring no DC bias in the receive/standby (distributed version)

Two diodes biased in series
No bias current needed during Rx
T/R switch requiring no DC bias in the receive/standby (lumped version)

Useful at lower frequency where $\lambda/4$ will be too long.
T/R, SPDT switch > 3 GHz

Only shunt switch elements due to poor isolation in series switch.
Minimalist T/R for class C PA – 1 PIN!

PIN turns on at Tx - L presents a hi-Z path to Tx power.

PIN off at Rx – series resonance of LC provide low Z path to LNA. Unbiased class C PA presents hi Z to Rx signal.

Doesn’t work > VHF due to PA parasitics.

\[ X_L \geq 200\Omega \]
\[ F = \frac{1}{2\pi \sqrt{LC}} \]
High isolation in "off" amplifier

Simply adding a PIN diode in series with the amplifying device output enables the "off" isolation to be improved without the addition of extra biasing components.
To achieve the highest isolation, alternate high/low impedances

- Use alternating series and shunt diodes for a small, high isolation switch
- Use $\lambda/4$ spacing for high isolation switches with the fewest components

Techniques for wideband applications.
High isolation 50 MHz SPDT switch, Version 1

Series switch elements only.

R value chosen to give 5-10mA through the "on" diodes.

If only unipolar control is available, the circuit can be easily reconfigured to operate from two differential control inputs.

<table>
<thead>
<tr>
<th></th>
<th>in1 to out</th>
<th>in2 to out</th>
</tr>
</thead>
<tbody>
<tr>
<td>control voltage</td>
<td>+ve</td>
<td>-ve</td>
</tr>
</tbody>
</table>
Shunt elements vastly improve the isolation performance.

R value chosen to give 5-10mA through the "on" diodes. (If R value is low, a series inductor will be needed if through loss is important.)

If only unipolar control is available, the circuit can be easily reconfigured to operate from two differential control inputs.

<table>
<thead>
<tr>
<th>control voltage</th>
<th>in1 to out</th>
<th>in2 to out</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ve</td>
<td>-ve</td>
<td></td>
</tr>
</tbody>
</table>
Other PIN switch applications

Bypass switch for mast mounted LNA

Diversity switch

Polarization/Band switcher in Sat-TV LNB
Application: Attenuator
The bulk PIN diode as an attenuator element

- bulk diodes
  - well controlled $R \propto I$ behavior
  - true current controlled resistor
  - low distortion
  - poor choice for switches because of high current consumption

$\text{p}$ and $\text{n}$ diffused into pure intrinsic silicon
The single shunt diode as an attenuator

- This simple structure offers wide dynamic range, but input return loss is excessive

![Diagram of the single shunt diode attenuator circuit with a graph showing forward current vs. input return loss and insertion loss in dB. The graph includes a logarithmic scale for forward current and a linear scale for return loss and insertion loss.]
The addition of two fixed resistors provides a reasonable return loss over a useful dynamic range.

Modified version of the 1 diode attenuator

![Attenuator Circuit Diagram]

![Graph showing Insertion loss and Input return loss vs Forward current]
A low current diode pair, three capacitors and two resistors can be combined to make a low current version of the one diode attenuator.
Constant input impedance attenuators < 2 GHz

The use of diode arrays, with proper bias networks, can provide wide dynamic range with constant return loss

Bridged TEE

TEE
Constant input impedance attenuators > 2 GHz

Because of the distributed nature, these circuits are generally too large to be useful at lower frequencies but are very useful above 1 GHz.
The four-diode $\pi$ attenuator

- The conventional $\pi$ attenuator is asymmetrical, leading to complex bias circuitry.
- The four-diode $\pi$ attenuator is symmetrical, using fewer bias components.
PI attenuator in SOT-25 package
Low loss/low voltage Pi attenuator with 3 ferrite beads

Frequency Vs. Attenuation at Vc = 5V for different no. of Ferrite Beads
0 FeBd 1 FeBd 3 FeBd

Start: 10.00 MHz Stop: 3.00 GHz
Attenuator with positive attenuation/voltage slope

![Diagram of attenuator with control voltage and voltage slope](image)

- RF in
- RF out
- λ/4
- control voltage
- +5V

Control Voltage, V vs. Attenuation, dB

- 0 dB
- 5 dB
- 10 dB
- 15 dB
- 20 dB
- 25 dB
- 30 dB

Control Voltage, V

- 1.5
- 2.0
- 2.5
- 3.0
- 3.5

June 2008
IEEE MTT/ED/SSCS Penang Chapter
3 dB quadrature coupler attenuator

- When $Z_2 = Z_3 = 50 + j0$, then $P_{out} = 0$ (high attenuation)
- When $Z_2 = Z_3 = $ open or short circuit ($\Gamma = 1$), then $P_{out}/P_{in} = 1$ (minimum loss)
- For best performance, $Z_2$ and $Z_3$ must track with each other as they vary
Quadrature coupler attenuator

- Depends on matched PIN diode pair.
- $A_{\text{max}}$ limited by coupler's directivity & low $\Gamma_{\text{load}}$. 
Measured data on experimental 1900 MHz attenuator

S11 < -19 dB over the attenuation range
S22 < -16 dB over the attenuation range
Attenuator with linear transfer curve

- Attenuation curve is straight on a linear plot.
- Return loss is high - minimize with circuit
Application: Limiter
Limiter

- Limiters - reducing the amplitude of an RF signal to protect a delicate circuit (such as an amplifier) which is downstream.
- Goes into low Z state during large signal – reflects power back to source.
- Use thin epi PIN diodes (t = 70nS) for low turn-on resistance.
Self-biased PIN limiter

- Inductor required to complete DC path – chosen for large $X_L$ and Self Resonance above operating frequency.
- Such circuits have output (leakage) powers on the order of +15 to +17 dBm.
Schottky assisted PIN limiter

For protecting more sensitive LNAs. Output (leakage) powers on the order of 2 to 5 dBm.
Reducing limiter loss at high frequency

Cut the microstrip line to integrate lead and bondwire inductances into a low pass filter structure.

\[ \text{Diagrams showing integration process} \]

\[ = \text{loss} \]

\[ = \text{low pass filter} \]
Application: Phase Shifter
0/180° phase shifter for low frequencies

- Parasitics mean that this solution will not work correctly at higher frequencies.

Diagram:
- RFin
- C
- control: 0deg: 0V, 180deg: +Vs
- RFout
- λ/2 or lumped element
0/180° phase shifter for 5.6 GHz, idea #1

Viability depends on board material.
0/180° phase shifter for 5.6 GHz, idea #2
Other uses

- Modulators – amplitude, phase & vector
- Frequency multiplier, comb generator
- Clamping/clipping