Basics of Diodes
(Power Losses and Thermal Design)

Outline:

Diodes are used in a wide range of equipment for various applications such as rectification, reverse-current blocking, and circuit protection. In addition to silicon (Si) pn diodes, various other types of diodes are available, including Schottky barrier diodes (SBDs), transient voltage suppressor (TVS) diodes (also known as ESD protection diodes), and Zener diodes. Toshiba's product portfolio also includes state-of-the-art silicon carbide (SiC) SBDs fabricated using a compound semiconductor. This application note discusses the power losses of and thermal design for diodes.

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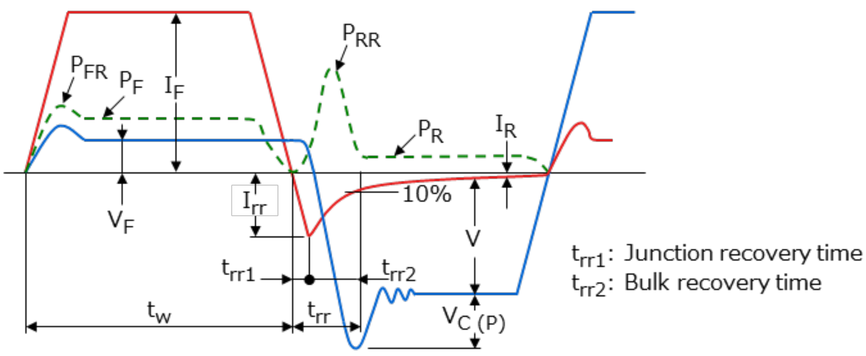


Figure 1.1 Example of a diode's switching waveform

(1) Forward power loss (P_F)

Normally, when a silicon (Si) diode is forward-biased, the forward voltage (V_F) decreases as temperature increases. The device temperature settles at a certain point. In the case of a silicon carbide (SiC) Schottky barrier diode (SBD), V_F has a positive temperature coefficient in the high-I_F region. It is therefore necessary to ensure that the rated forward power dissipation and junction temperature are not exceeded.

(2) Reverse power loss (P_R)

The power loss due to reverse leakage current (I_R) is negligibly smaller than forward power loss at low temperature. However, since I_R increases exponentially with temperature, the power loss due to I_R cannot be ignored at high temperature. Furthermore, if self-heating caused by I_R exceeds the heat dissipation capability of a diode, thermal runaway might occur. Regarding reverse power loss, it is necessary to allow sufficient margin for the maximum rated junction temperature and thermal runaway.

Si SBDs and fast rectifier diodes have higher I_R than typical rectifier diodes. In particular, a rise in temperature and an increase in current during operation make Si SBDs susceptible to thermal runaway, possibly leading to device destruction. For Si SBDs and fast rectifier diodes, it is necessary to calculate the power dissipation at high temperature, taking forward and reverse power losses into consideration, and use it as a basis for thermal and safety design. In addition, it is essential to perform verification using actual hardware to ensure that it works properly under the worst-case condition.

(3) Forward switching loss (P_{FR})

The forward switching loss (P_{FR}) is the loss that occurs when a rapidly rising rectangular wave pulse is applied to a diode in the forward direction.

The application of a pulse causes a diode's forward voltage to rise instantaneously above the steady-state forward voltage (V_F), increasing power dissipation (see Figure 1.1).

When a rapidly rising pulse is applied to a diode, it does not enter a conducting state immediately because carriers are not accumulated. During a certain period, a diode exhibits high resistance even in the forward direction. This phenomenon is called forward recovery. The forward recovery time (t_{fr}) is not dependent on the operating frequency, but on the rise time.

(4) Reverse switching loss (P_{RR})

The reverse switching loss (P_{RR}) is the loss that occurs when a rapidly rising reverse voltage pulse is applied to a diode. A power loss occurs while reverse current flows during the reverse recovery time (t_{rr}) since it cannot be blocked immediately (see Figure 1.1). The reverse switching loss (P_{RR}) is approximated as follows:

$$P_{RR} \simeq \frac{1}{2} i_{rr} \cdot t_{rr} \cdot V_R \cdot f = Q_R \cdot V_R \cdot f \qquad \text{(1-1)}$$

i_{rr}	:	Peak reverse current	(A)
t_{rr}	:	Reverse recovery time	(s)
V_R	:	Reverse voltage (in a steady state)	(V)
Q_R		Accumulated charge	(C)
f		Frequency	(Hz)

A power loss occurs during the t_{rr2} period of t_{rr}. Since the power loss during t_{rr1} is small, Equation 1-1 can be approximated as:

$$P_{RR} \simeq \frac{1}{6} i_{rr} \cdot t_{rr2} \cdot V_R \cdot f \qquad \text{(1-2)}$$

i_{rr}	:	Peak reverse current	(A)
t_{rr2}	:	Bulk recovery time	(s)
V_R	:	Reverse voltage (in a steady state)	(V)
f		Frequency	(Hz)

2. Thermal design

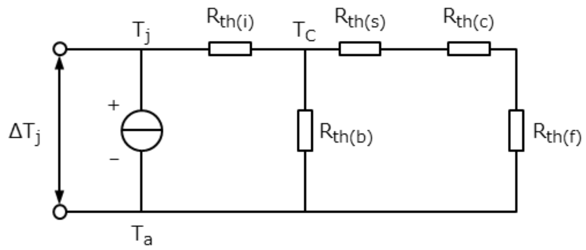
2.1. Maximum allowable power dissipation and equivalent thermal circuit

The power dissipation of a diode is a function of ambient temperature (T_a), case temperature (T_c), junction-to-ambient thermal resistance ($R_{th(j-a)}$), junction-to-case thermal resistance ($R_{th(j-c)}$), and maximum junction temperature ($T_{j(max)}$) as expressed by Equations 2-1 and 2-2:

$$P_{C(max)(T_a)} = \frac{T_{j(max)} - T_a}{R_{th(j-a)}} \quad \cdots\cdots \quad (2\text{-}1)$$

$$P_{C(max)(Tc)} = \frac{T_{j(max)} - T_C}{R_{th(j-c)}} \quad \cdots\cdots \quad (2\text{-}2)$$

A heat flow can be modeled by analogy to an electrical circuit. Using this model, the heat flow from the junction of a diode to the ambient air is derived from thermal resistances and thermal capacitances. Figure 2.1 shows an equivalent thermal circuit in a thermally steady state.



$R_{th(i)}$: Junction-to-case thermal resistance

$R_{th(b)}$: Case-to-ambient thermal resistance

$R_{th(s)}$: Thermal resistance of silicone grease or TIM[*1]

$R_{th(c)}$: Contact thermal resistance between case and heatsink

$R_{th(f)}$: Thermal resistance of a heatsink

Figure 2.1 Equivalent thermal circuit

*1 Thermal interface material (TIM)

From the equivalent circuit of Figure 2.1, the junction-to-ambient thermal resistance ($R_{th(j-a)}$) can be calculated as follows:

$$R_{th(j-a)} = R_{th(i)} + \frac{R_{th(b)} \cdot \left(R_{th(s)} + R_{th(c)} + R_{th(f)}\right)}{R_{th(b)} + R_{th(s)} + R_{th(c)} + R_{th(f)}} \quad \cdots\cdots \quad (2\text{-}3)$$

The $R_{th(j-a)}$ of a diode without a heatsink can be calculated as follows:

$$R_{th(j-a)} = R_{th(i)} + R_{th(b)} \quad \cdots\cdots \quad (2\text{-}4)$$

The datasheets for diodes without a heatsink show their maximum allowable power dissipation at an ambient temperature (T_a) of 25°C. Unless specifically otherwise noted, this is calculated as follows from $R_{th(j-a)}$ given by Equation 2-4 and $T_{j(max)}$:

$$P_{C(max)(T_a=25°C)} = \frac{T_{j(max)} - 25}{R_{th(j-a)}} \quad \cdots\cdots \quad (2\text{-}5)$$

The case-to-ambient thermal resistance ($R_{th(b)}$) varies with the materials and shape of the case. Generally, $R_{th(b)}$ is significantly larger than $R_{th(i)}$, $R_{th(c)}$, $R_{th(s)}$, and $R_{th(f)}$. Therefore, Equation 2-3 can be simplified to:

$$R_{th(j-a)} = R_{th(i)} + R_{th(c)} + R_{th(s)} + R_{th(f)} \quad \cdots\cdots \quad (2\text{-}6)$$

Equation 2-6 can be used to create a thermal design that satisfies the maximum rating requirement for DC dissipation. When diodes are used in a switching circuit, great care is required to ensure that the peak T_j value does not exceed $T_{j(max)}$.

2.2. Thermal resistance

The thermal resistance values shown in the equivalent thermal circuit of Figure 2.1 can be explained as follows:

(1) Junction-to-case thermal resistance (internal thermal resistance): $R_{th(i)}$

The internal thermal resistance ($R_{th(i)}$) from the junction of a diode to the case depends on the structure and material of the diode and differs from diode to diode. To measure internal thermal resistance, the case of the diode must be cooled to maintain a constant temperature. When the case temperature (T_c) is held at 25°C, the maximum allowable power dissipation ($P_{C\,(max)}$) of a diode can be calculated as follows:

$$P_{C(max)} = \frac{T_{j(max)} - T_C}{R_{th(i)}} = \frac{T_{j(max)} - 25}{R_{th(i)}} \quad \cdots\cdots \quad (2\text{-}7)$$

In the datasheets for diodes that can be attached to a heatsink, the maximum allowable power dissipation is specified either at T_C = 25°C or assuming the use of an infinite heatsink. $P_{C(max)}$ is determined by the internal thermal resistance of the diode as indicated by Equation 2-7.

(2) Contact thermal resistance: $R_{th(c)}$

Contact thermal resistance ($R_{th(c)}$) varies according to the condition of the contact surface between the case of a diode and a heatsink. This condition is greatly affected by factors such as the evenness, coarseness, and area of contact, as well as the attachment of the diode to the heatsink. The influence of the coarseness and unevenness of the contact surface can be reduced by using silicon grease or TIM.

(3) Isolation plate’s thermal resistance: $R_{th(s)}$

If it is necessary to provide electrical isolation between a diode and a heatsink, an isolation plate must be inserted between them. The thermal resistance of this isolation plate ($R_{th(s)}$) varies with the materials, thickness, and area of the plate and is not negligible.
For packages isolated by mold resin, the thermal resistance specified for a diode includes the insulator's thermal resistance ($R_{th(s)}$).

(4) Heatsink's thermal resistance: $R_{th(f)}$
The thermal resistance of a heatsink can be considered as the distributed thermal resistance of a heat path from the surface of a heatsink to the ambient air. The thermal resistance of a heatsink depends on the condition of the ambient air, a difference in temperature between the heatsink and the ambient air, and the effective area of the heatsink. It is difficult to mathematically express $R_{th(f)}$. Actually, $R_{th(f)}$ is obtained by measurement. Figure 2.2 shows an example of thermal resistance data measured for a diode at the center of a vertically standing heatsink. Various heatsinks are available from many vendors. Optimal heatsinks should be selected, referring to their technical datasheets.

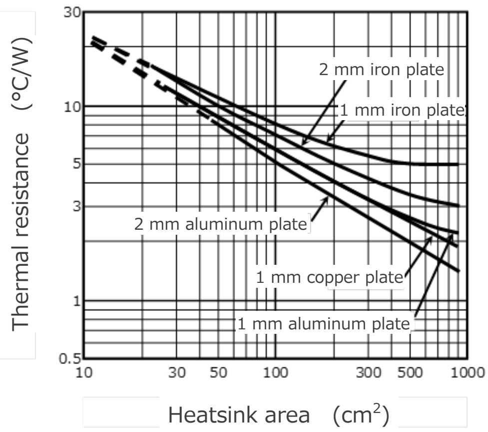


Figure 2.2 Example of thermal resistance-vs-heatsink area curves

2.3. Pulse response of junction temperature

Generally, the thermal impedance of a diode is modeled as a distributed constant circuit as shown in Figure 2.3.

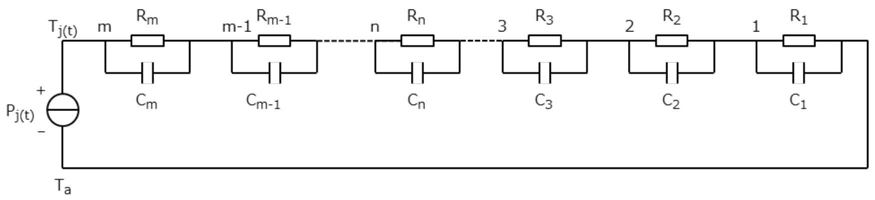


Figure 2.3 Thermal impedance model

When the pulsed power dissipation ($P_{j(t)}$) shown in Figure 2.4 is applied to the circuit of Figure 2.3, a change in junction temperature ($T_{j(t)}$) that appears at the mth parallel RC circuit under stable thermal conditions can be calculated as follows.

In region (a) where $P_{j(t)} = P_0$:

$$T_{j(t)} = \sum_{n=1}^{m}\left\{(P_O \cdot R_n) - T_{n(min)}\right\}\left(1 - exp^{-\frac{t}{C_n \cdot R_n}}\right) + T_{n(min)}$$

·········· (2-8)

In region (b) where $P_{j(t)} = 0$

$$T_{j(t)} = \sum_{n=1}^{m}\left\{T_{n(max)} \cdot exp^{-\frac{t}{C_n \cdot R_n}}\right\} \quad \cdots\cdots\cdots\cdot \text{(2-9)}$$

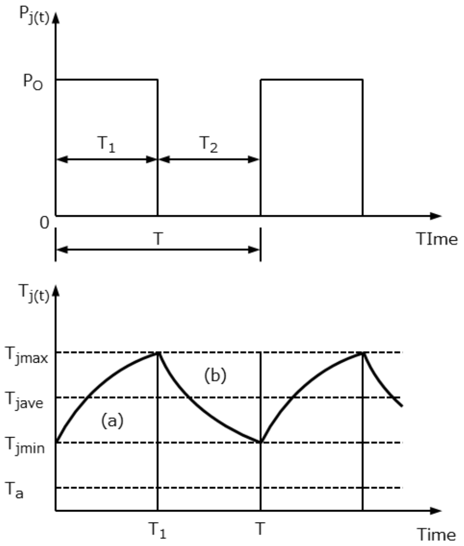


Figure 2.4 Change in junction temperature caused by pulsed power dissipation

For typical diodes, the actual $P_{j(t)}$ value can be approximated by substituting 4 for m. However, if the C and R values are indefinite, it is difficult to calculate T_j. Therefore, $T_{j(max)}$ is generally estimated using transient thermal resistance as shown in Figure 2.5.

Suppose that a single-shot pulsed rectangular power dissipation (with a pulse width of t and a peak value of P_O) is applied. From the figure, we read the transient thermal impedance ($r_{th(t)}$) at a pulse width of t, and then use Equation 2-10 to calculate $T_{j(max)}$.

$$T_{j(max)} = r_{th(t)} \cdot P_O + T_a \quad \cdots\cdots \text{(2-10)}$$

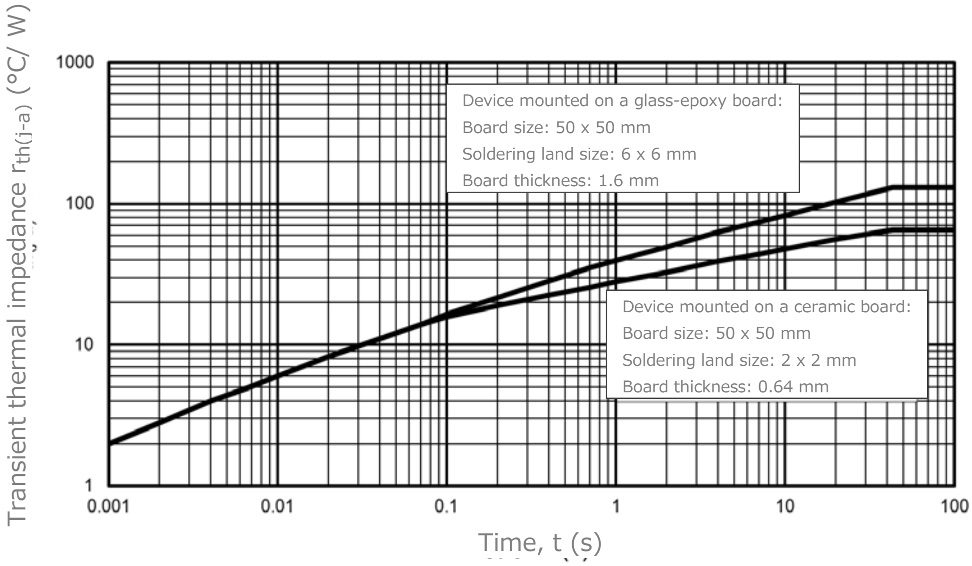


Figure 2.5 Example of transient thermal impedance curves

When a repetitive pulse train with a cyclic period of T is applied as shown in Figure 2.6, $T_{j(max)}$ is given by Equation 2-15 using the superposition theorem.

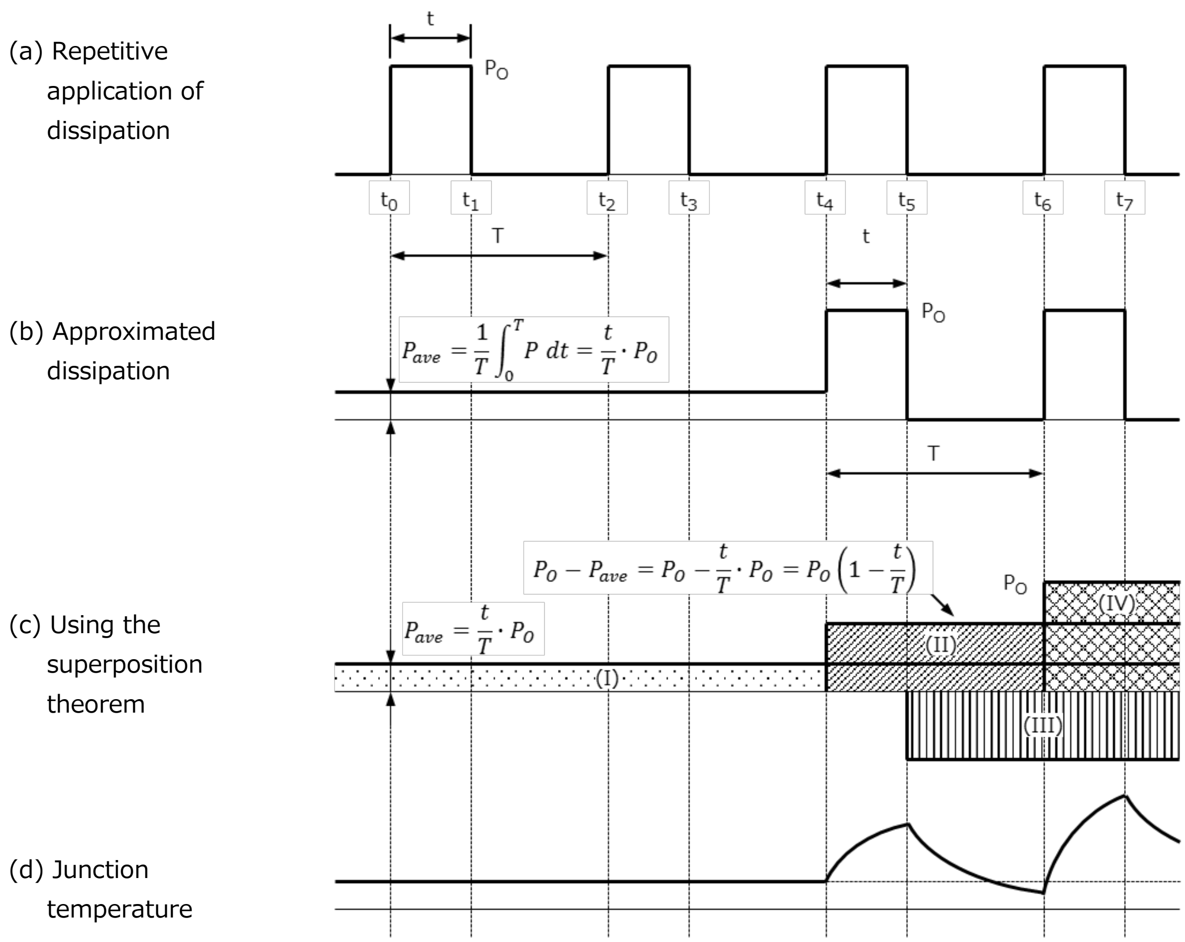


Figure 2.6 Change in junction temperature caused by repetitive application of rectangular pulsed power dissipation at a cyclic period of T

Rise in junction temperature in region (I)

$$\Delta T_{j(I)} = P_O \cdot \frac{t}{T} \cdot R_{th(j-a)} \quad \cdots\cdots \quad (2\text{-}11)$$

Rise in junction temperature in region (II)

$$\Delta T_{j(II)} = P_O \cdot \left(1 - \frac{t}{T}\right) \cdot r_{th(T+t)} \quad \cdots\cdots \quad (2\text{-}12)$$

Rise in junction temperature in region (III)

$$\Delta T_{j(III)} = -P_O \cdot r_{ch(T)} \quad \cdots\cdots \quad (2\text{-}13)$$

Rise in junction temperature in region (IV)

$$\Delta T_{j(IV)} = P_O \cdot r_{th(t)} \quad \cdots\cdots \quad (2\text{-}14)$$

From Equations 2-11 to 2-14, the maximum junction temperature ($T_{j(max)}$) can be calculated as:

$$T_{j(max)} = P_O \cdot \left\{ \frac{t}{T} \cdot R_{th(j-a)} + \left(1 - \frac{t}{T}\right) \cdot r_{th(T+t)} - r_{th(T)} + r_{th(t)} \right\} + T_a \quad \cdots\cdots\cdots\cdots \quad (2\text{-}15)$$

Great care should be exercised in the thermal design for pulsed power applications to ensure that $T_{j(max)}$ given by Equation 2-15 does not exceed the maximum rated junction temperature of the diode.

The above description assumes that a rectangular waveform is applied to a diode. However, for actual diode applications, the $P_{j(t)}$ waveform seldom becomes rectangular. In such cases, approximate the power dissipation waveform to a rectangular wave as shown in Figure 2.7 and use Equation 2-15 to estimate $T_{j(max)}$.

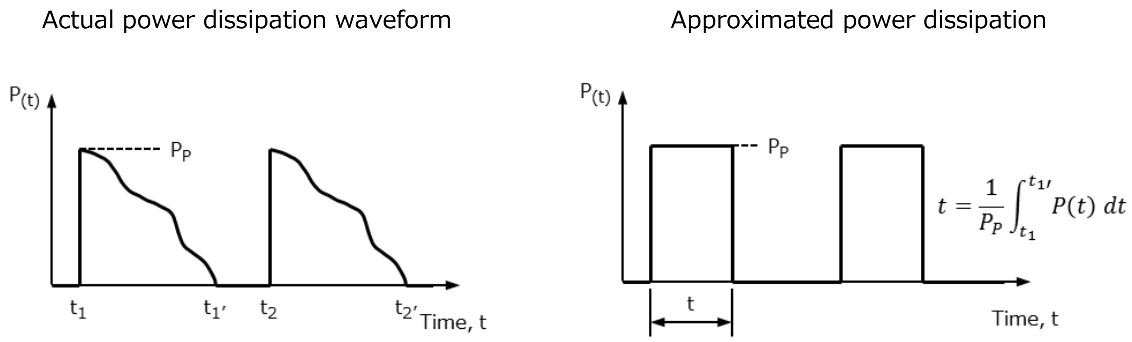


Figure 2.7 Approximation of a power dissipation waveform

Sine and triangular waves can be approximated to rectangular waves as shown in Figure 2.8. To obtain a rectangle with an area equal to a half-sine or triangular area, multiply the peak value of P_P by 0.7 in the case of (a) and (b), and multiple the pulse width by 0.91 for (a) and by 0.71 for (b). In the case of (c) and (d), use the same peak value of P_P, and multiply the pulse width by 0.63 for (c) and by 0.5 for (d).

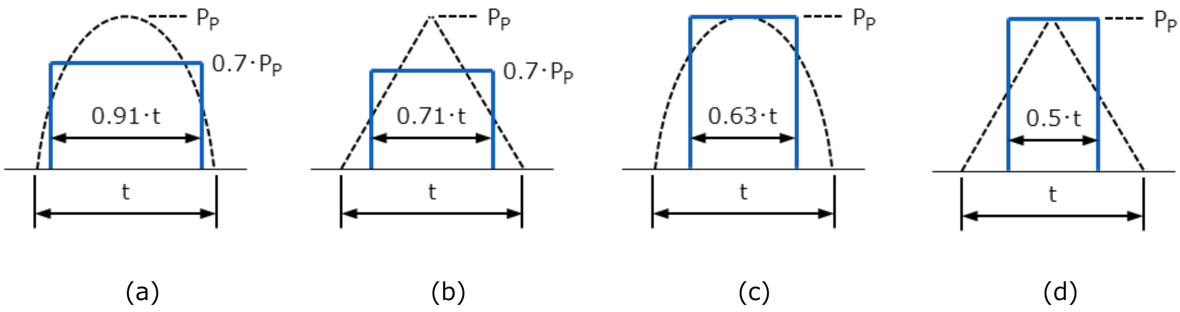


Figure 2.8 Approximating sine and triangular waves to rectangular waves

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