Technical Article

Why Class D Amplifiers Need Anti-Parallel Diodes

5 days ago by Dr. Steve Arar

Learn how anti-parallel diodes protect Class D amplifiers from the effects of reactive loads and inductive kickback.

The previous article in this series introduced the Class D amplifier. In that article, we mostly ignored non-idealities in favor of examining the underlying principles of switching-mode amplifier operation. Now that we've covered the basics, we can move from principles to practicalities.

For example, we previously assumed that the resonant frequency of the amplifier's tuned circuit was equal to the switching frequency. In practice, the resonant frequency and switching frequency may be slightly different. For the Class D amplifier to operate as expected, we need to include anti-parallel diodes. The diodes also help prevent damage to the transistors.

In this article, we'll explore the role of anti-parallel diodes in Class D operation when the switching frequency is slightly above the resonant frequency. First, though, there are some key features of ideal operation we need to highlight.

Class D Amplifier With A Perfectly Tuned LC Circuit

Consider the complementary voltage-switching Class D amplifier in Figure 1. We first saw this configuration in the preceding article.

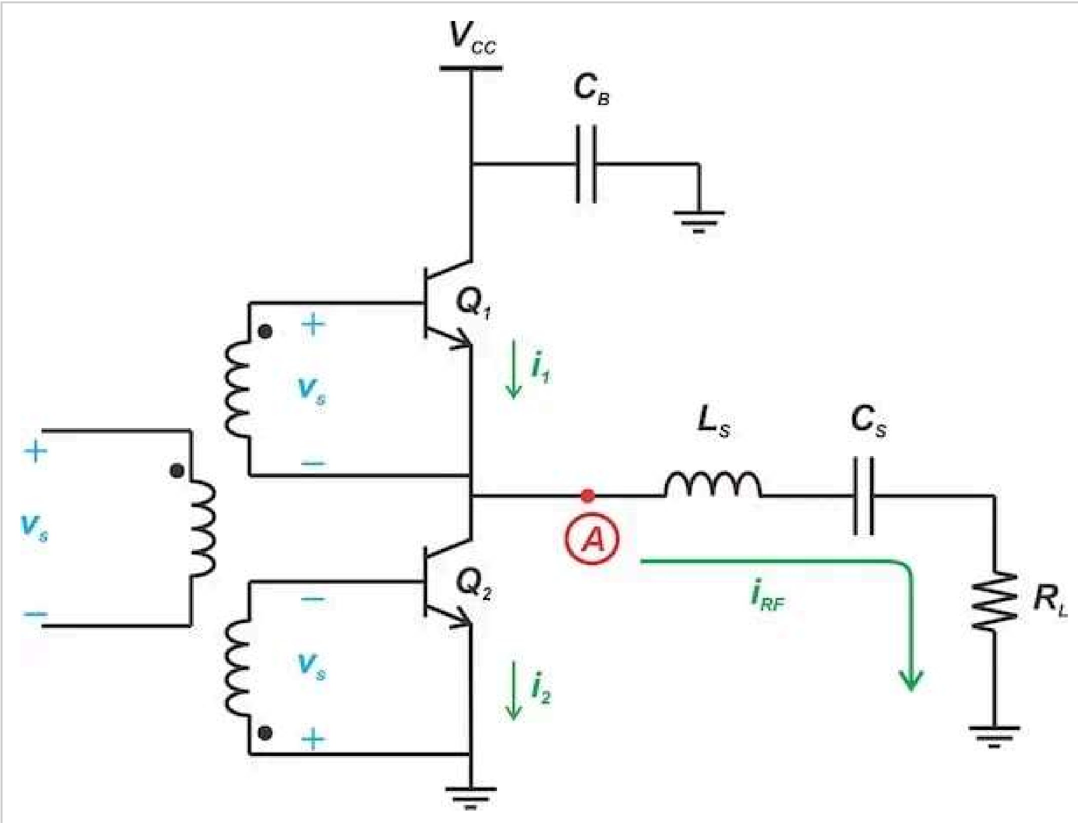

Figure 1. Complementary voltage-switching configuration. Image used courtesy of Steve Arar

Assuming that the transistors act as ideal switches, the voltage at node A is a square wave (Figure 2).

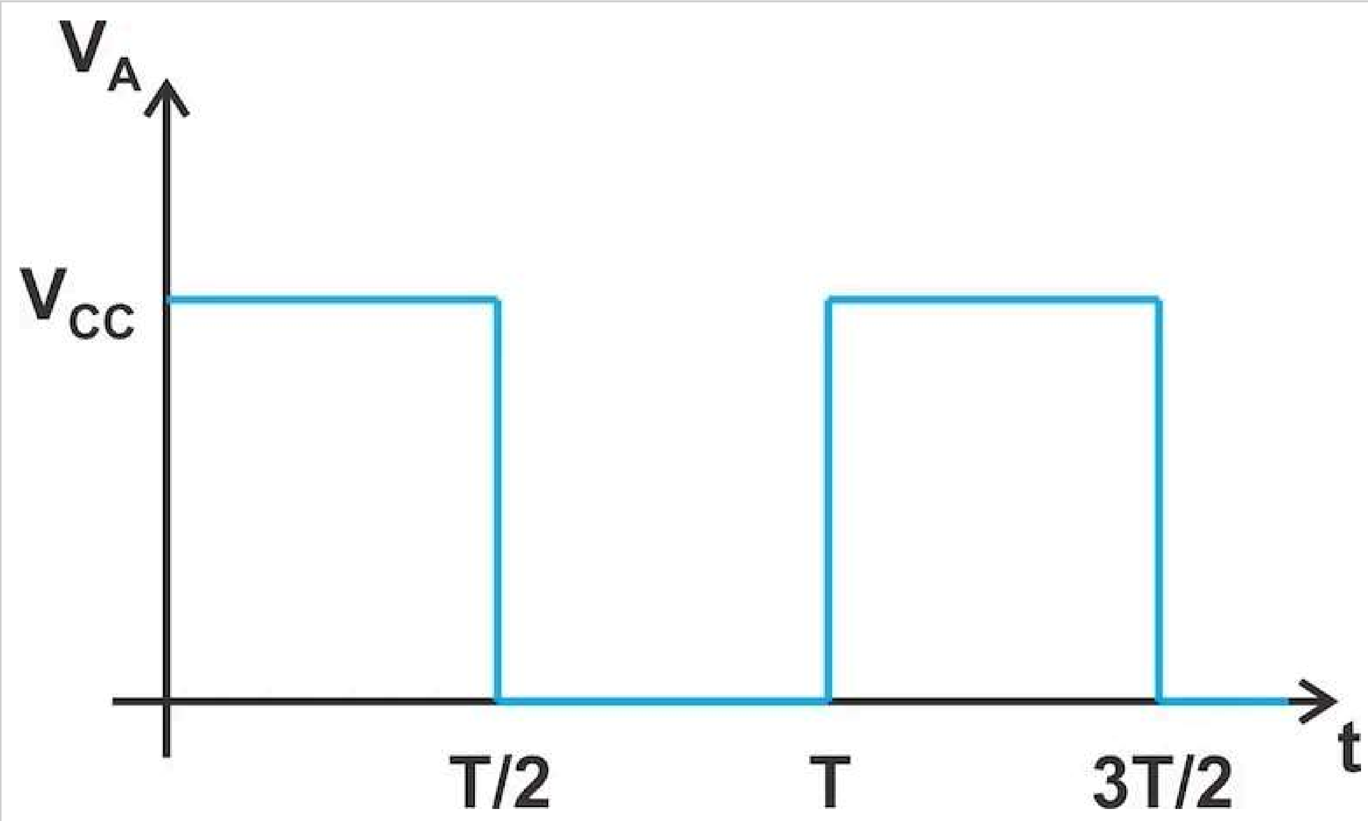

Figure 2. The square wave at the input of the series LC circuit. Image used courtesy of Steve Arar

With a high-Q tuned circuit, only the fundamental component of the square wave can produce a current through the LC circuit. Other components see a large impedance and can't produce harmonic currents. In the rest of this article, we'll focus only on the output current's fundamental component.

At the resonant frequency, the reactances of L_s and C_s cancel each other out, producing a resistive load (R_L) at node A. Assuming that the switching frequency matches the resonant frequency of the tuned circuit, we have a resistive load at the switching frequency. This means that the output current is in phase with the fundamental component of the square wave. Figure 3, which shows the current waveform for the fundamental component, confirms this.

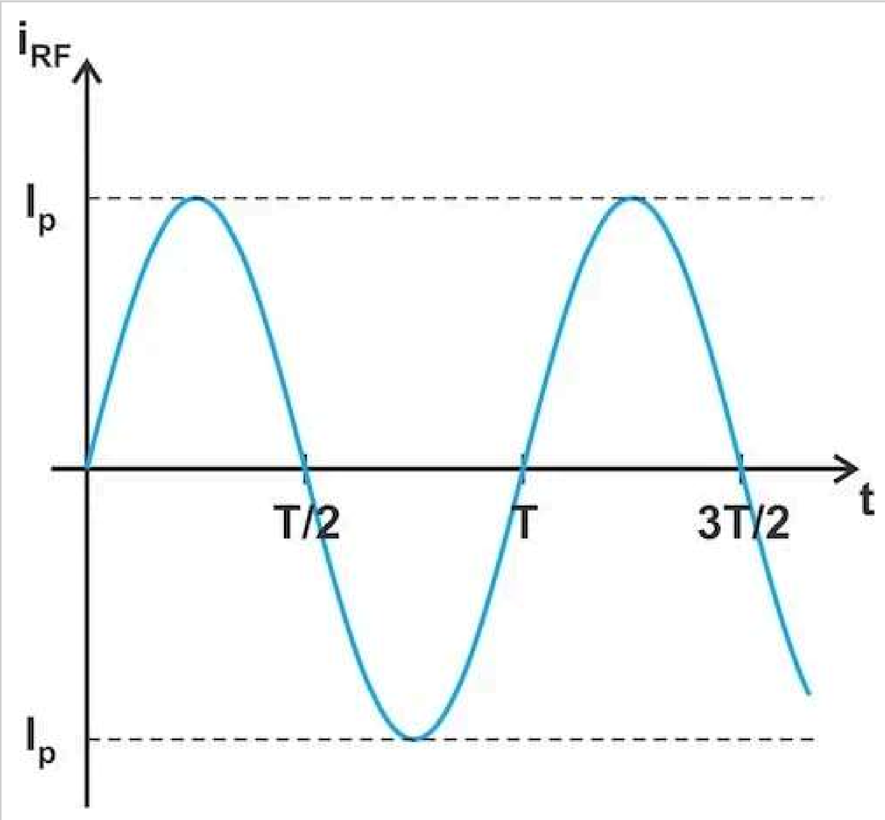

Figure 3. A sinusoidal current at the fundamental frequency flows through the LC circuit. Image used courtesy of Steve Arar

The upper switch (Q_1) is ON during the (0, *T*/2) time interval. As we see in Figure 3, the output current (i_{RF}) is always positive in this interval. Therefore, the current provided by the transistor Q_1 is also always positive.

The output current in Figure 3 is negative during the (*T*/2, *T*) time interval, which is when the lower switch (Q_2) is ON. If we consider the current directions in Figure 1, however, we observe that the current drawn by the transistor Q_2 is always positive.

The two halves of Figure 4 illustrate the currents that flow through Q_1 and Q_2, respectively. Figure 4(a) shows the waveform for i_1, the current that flows through the upper switch (Q_1). Figure 4(b) shows i_2, the current through the lower switch (Q_2).

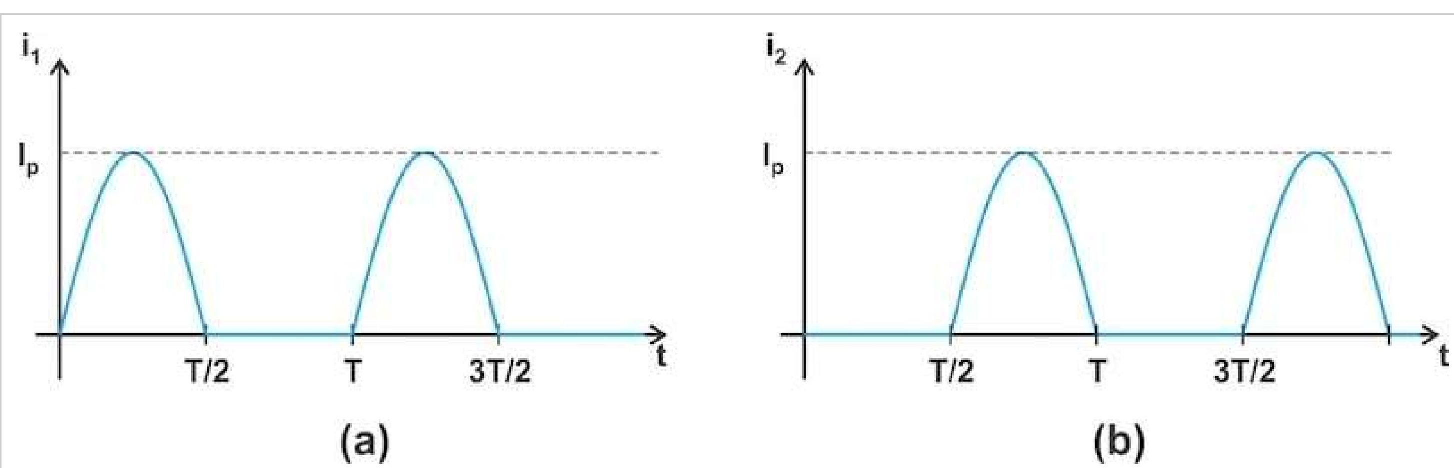

Figure 4. The currents flowing through the upper (a) and lower (b) switches. Image used courtesy of Steve Arar

To summarize, currents passing through the transistors are positive when the switching frequency matches the resonant frequency. This simplifies the circuit implementation of the Class D configuration. In practice, however, the switching frequency *isn't* exactly the same as the resonant frequency. Let's examine the effects of this mismatch on the amplifier's performance.

Reactive Loads: Operating a Class D Amplifier Above Its Resonant Frequency

The current flowing through an inductor lags behind the voltage across it by exactly 90 degrees. In a Class D amplifier operating even slightly above its resonant frequency, the series LC circuit is primarily inductive. The fundamental component of the output current therefore lags behind the fundamental component of the square wave (V_A), as we see in Figure 5. However, because the inductive LC component is in series with a resistive load, the phase difference is less than 90 degrees.

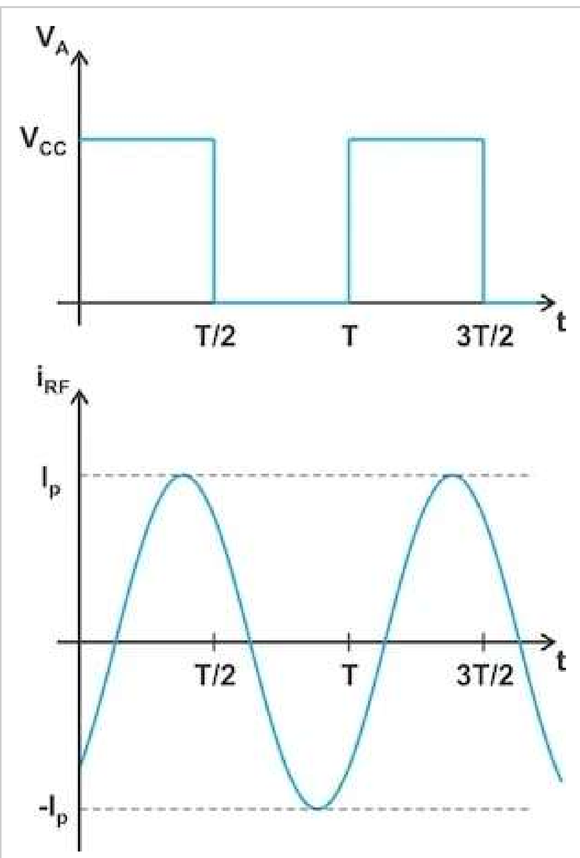

Figure 5. Above the resonant frequency, the current lags the fundamental component of the voltage. Image used courtesy of Steve Arar

How does this phase mismatch between the square wave and i_{RF} affect the currents flowing through the switches? Consider Figure 6(a) and 6(b). Figure 6(a) shows the current (i_{sw1}) passing through the upper switch; Figure 6(b) shows the current (i_{sw2}) passing through the lower switch. These two currents combine to produce the i_{RF} waveform of Figure 5.

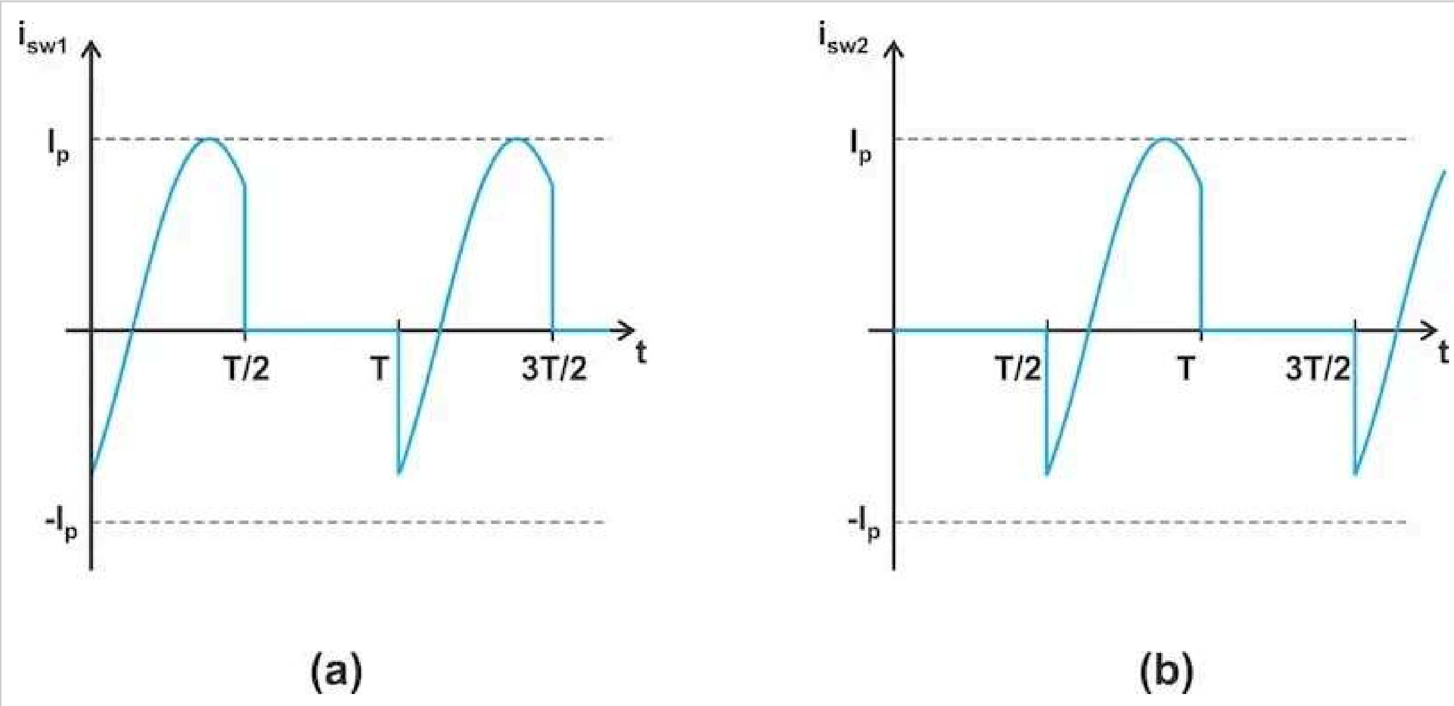

Figure 6. The currents flowing through the upper switch (a) and lower switch (b) when the Class D amplifier operates above its resonant frequency. Image used courtesy of Steve Arar

Each switch conducts negative currents during part of its ON cycle. The circuit diagram in Figure 1 shows that our switches, Q_1 and Q_2, are bipolar junction transistors. Since BJTs can't conduct reverse currents, we commonly use anti-parallel diodes to provide a path for negative currents. This is illustrated in Figure 7.

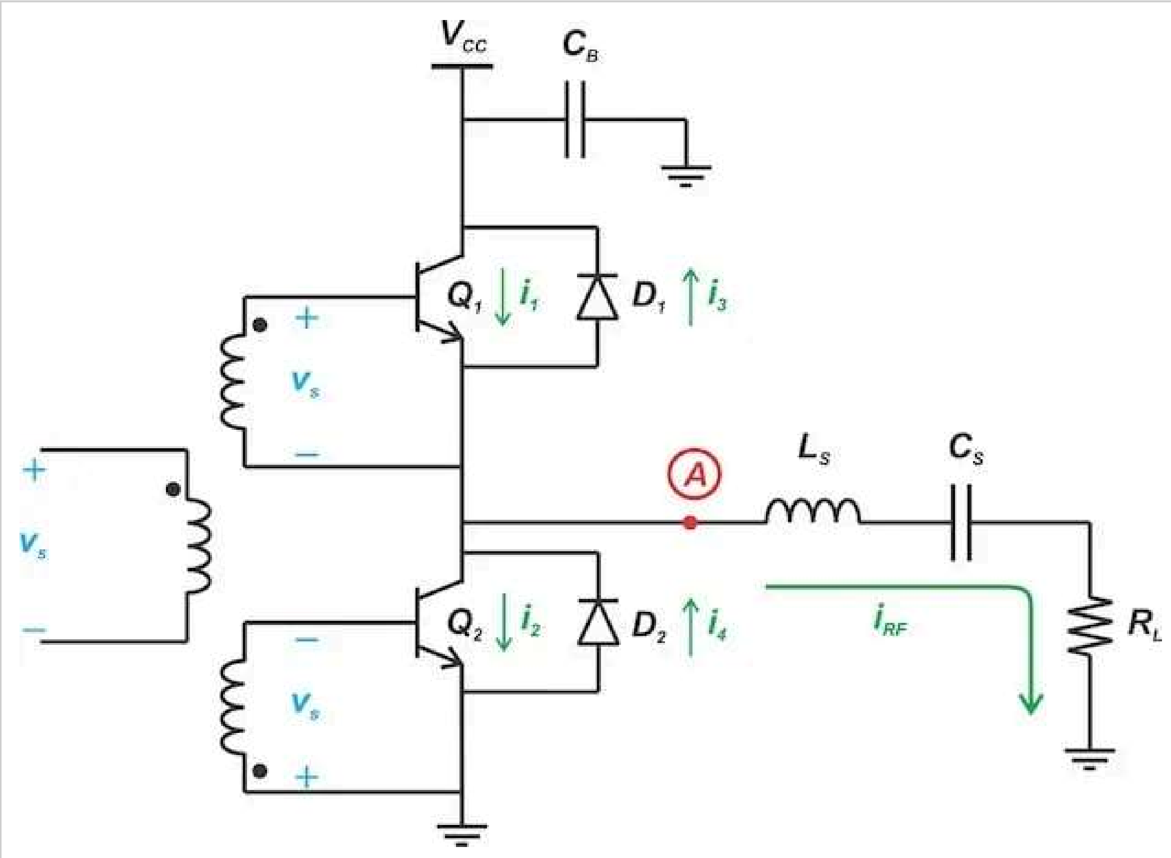

Figure 7. A complementary voltage-switching Class D amplifier with anti-parallel diodes to conduct the negative currents. Image used courtesy of Steve Arar

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Diodes D_1 and D_2 act as switches that automatically turn on when required, which is interesting when you think about it. The output current is provided by one of the four devices: Q_1, Q_2, D_1, or D_2. The devices work together as follows:

- D_1 passes the negative portion of i_{sw1}.
- Q_1 passes the positive portion of i_{sw1}.
- D_2 passes the negative portion of i_{sw2}.
- Q_2 passes the positive portion of i_{sw2}.

Figure 8(b) and 8(a) show the currents passing through D_1 and Q_1, respectively. Figure 8(d) and 8(c) show the currents passing through D_2 and Q_2.

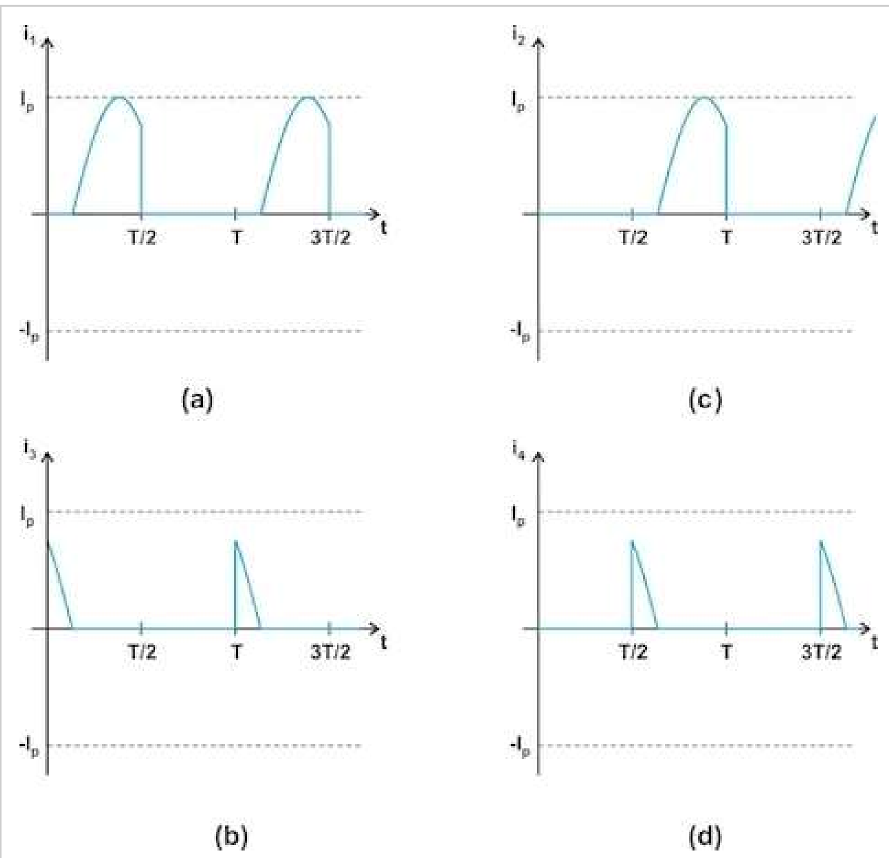

Figure 8. The currents passing through Q_1 (a), D_1 (b), Q_2 (c), and D_2 (d). Image used courtesy of Steve Arar

Please note that Figure 8 is organized such that plot (a) corresponds to current i_1, plot (b) to current i_2, (c) to i_3, and (d) to i_4. It does not represent the sequence in which the devices turn on. The turn-on order is given in the bulleted list above the figure: D_1, Q_1, D_2, Q_2.

Along with providing a path for reverse currents, anti-parallel diodes play another key role in Class D amplifiers. As we'll discuss in the next section, they protect the transistors against voltage spikes.

How Diodes Protect the Transistors in a Class D Amplifier

Referring back to the circuit diagram in Figure 7, large voltage spikes can appear at node A. To understand this, recall that inductors resist rapid changes in their currents. Forcing a rapid change in the inductor current through the switching action induces a large voltage across its terminals, a phenomenon known as inductive kickback.

For example, assume that we abruptly cut off the current of a 10 mH inductor from 10 mA to zero in a time interval of 10 ns. The inductor will induce a voltage of –10,000 V across it, as calculated below:

$$V = L\frac{dI}{dt} \approx 10\ \text{mH} \times \frac{(0 - 10)\ \text{mA}}{10\ \text{ns}} = -10,000\ \text{V}$$

Generally, inductor currents are switched using either a mechanical switch or a transistor. For mechanical switches, inductive kickback ionizes the air between the switch contacts, causing bright sparks. With transistors, the large voltage from the inductive kickback can easily damage the transistor.

To circumvent the rapid changes in current that cause inductive kickback, we use diodes to create a current path. The anti-parallel diodes in the Class D amplifier provide this functionality.

For example, let's examine the instant $t = T/2$ in Figure 8's current waveforms. For convenience, the currents of interest (i_1 and i_4) are reproduced below in Figure 9.

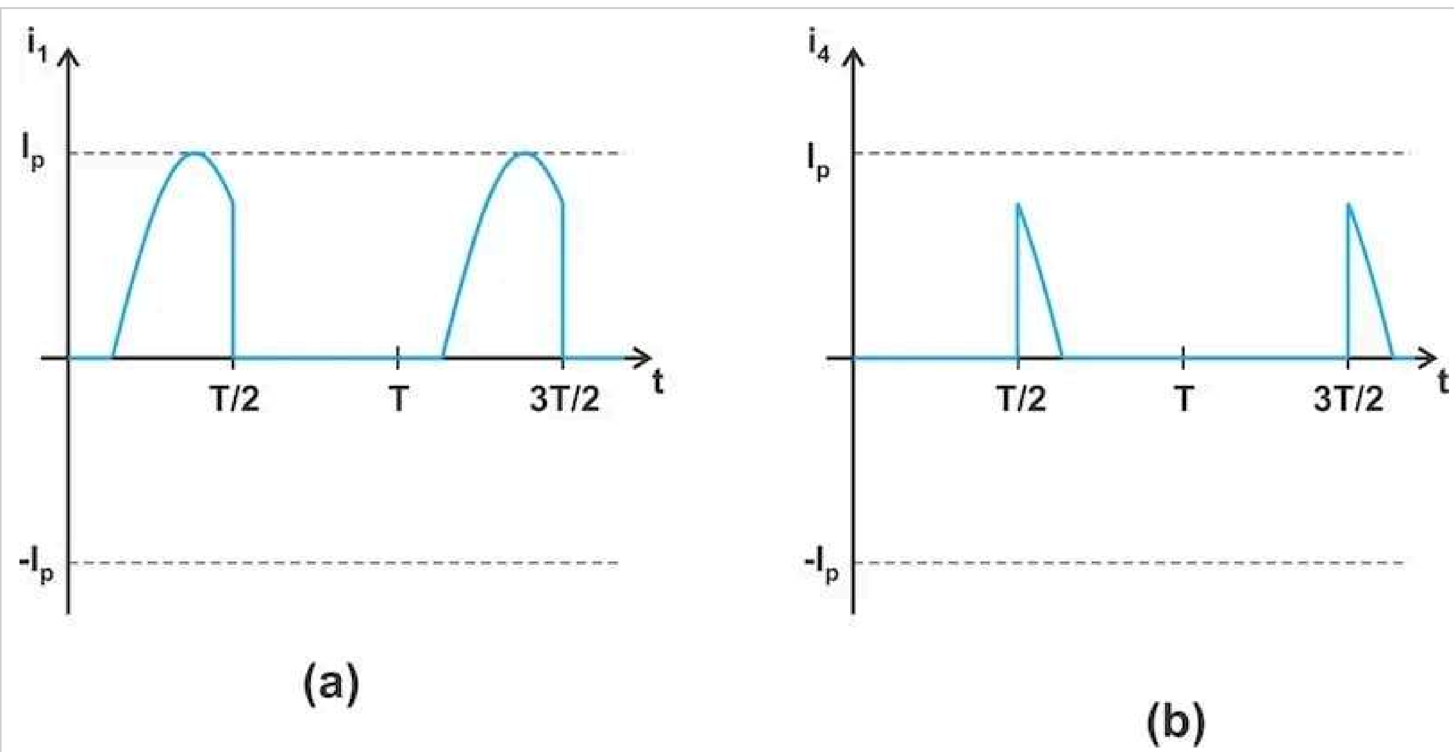

Figure 9. Current is diverted from the upper transistor to the lower diode at t = T/2. *Image used courtesy of Steve Arar*

Before switching occurs, the transistor Q_1 sources some positive current. Without the anti-parallel diodes, switching would cut off this current to zero and produce a negative voltage spike at node A, damaging the transistors.

However, with D_2 in place, the voltage spike can't go below about –0.7 V, as determined by the forward drop of D_2. When the voltage at node A reaches –0.7 V, D_2 turns on and creates a path for the inductor current. Similarly, D_1 turns on to provide a path for the inductor current when we turn off Q_2 at $t = T$.

MOSFET Switches

We can also use MOSFETs instead of bipolar junction transistors to implement the switches of the Class D amplifier. Figure 10 shows the cross-section of a power MOSFET.

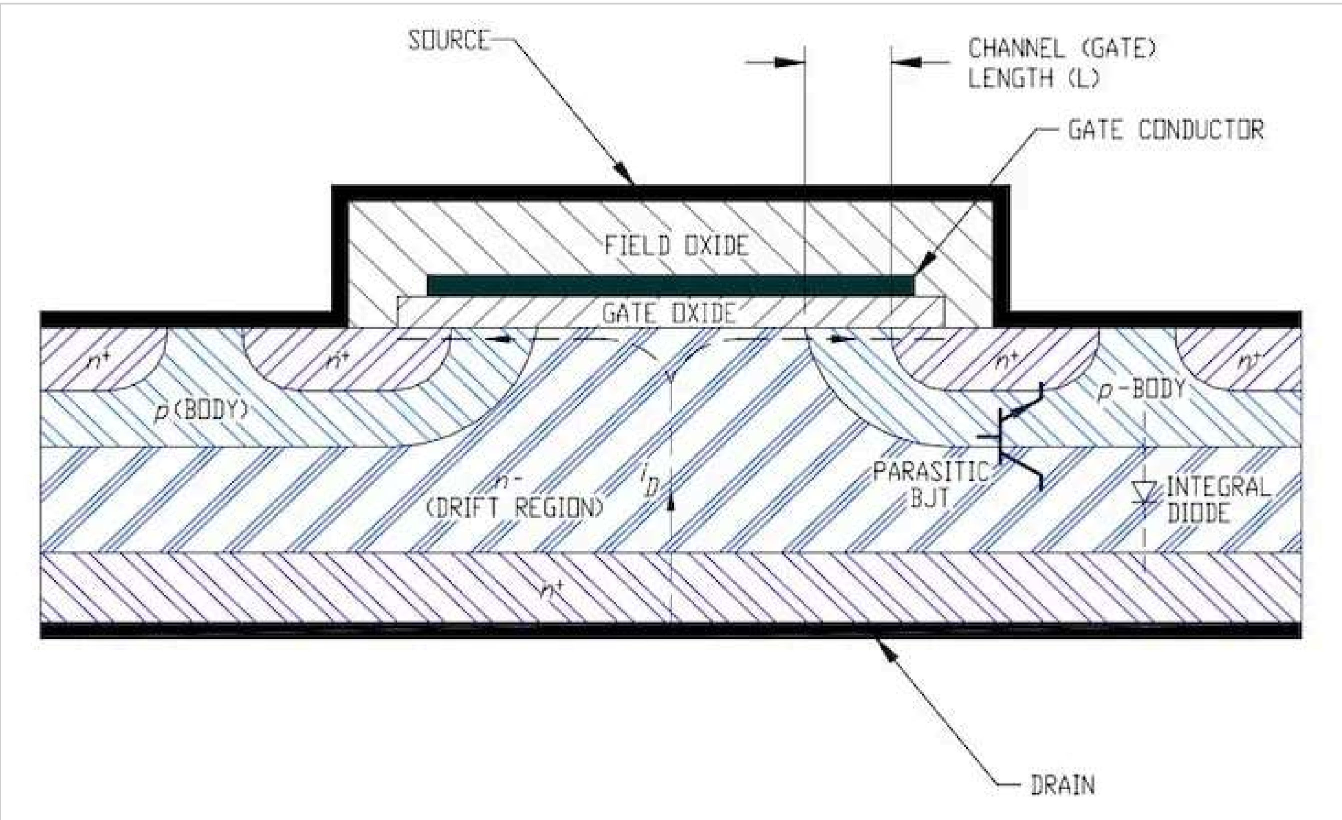

Figure 10. Structure of an N-channel power MOSFET. Image used courtesy of [*IXYS*]

With this structure, the current flows vertically through the silicon wafer. At the bottom of the wafer, we have the metallized drain connection. On the top of the wafer, we have the metallized source connection and the polysilicon gate.

When the drain-source voltage is positive, the P-N^- and P-N^+ junctions are reverse-biased. In this case, a sufficiently large gate-to-source voltage forms a channel underneath the gate and turns on the transistor to conduct current from the drain to the source. However, as the figure illustrates, a parasitic diode is created between the *P* and *N* regions.

This diode, known as the body diode, appears between the source and drain terminals. The body diode turns on and conducts current from the source to the drain when the drain-source voltage is negative. This happens regardless of the gate-to-source voltage.

Due to the body diode, MOSFET implementations of voltage-switching Class D amplifiers can operate without employing external anti-parallel diodes. Though MOSFETs pass reverse currents without risking damage, however, we still sometimes use external diodes to optimize amplifier performance.

The Importance of the Device Conduction Sequence

As we discussed earlier in the article, the amplifier's four semiconductor devices turn on in the following order:

$$D_1 \rightarrow Q_1 \rightarrow D_2 \rightarrow Q_2$$

Each transistor is turned on after its own anti-parallel diode.

Diodes can't instantly turn off. As they transition from forward to reverse bias, they pass some current in the reverse direction. This phenomenon is known as reverse recovery. An important advantage of the above conduction sequence is that the reverse recovery currents of the diodes become part of the positive switch current.

In the next article, we'll explore in detail how reverse recovery influences the performance of Class D amplifiers. In the course of this discussion, we'll also examine the operation of the amplifier when the switching frequency is below the resonant frequency. This causes a capacitive load; as we'll see next time, it also changes the turn-on sequence, causing a large reverse recovery loss.

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