Understanding The Operation of a CRT Monitor

Computer technology is going to see major advances in the 1990s. Users will see desk top computers with the computational power of today's super-computers. Even graphics capabilities for sophisticated 3 dimensional modeling and image processing would be available to the average user at a reasonable cost. In the area of electronic publishing; users will be able to store video images in the computer, merge the images with text and graphics and produce true color photorealistic hardcopies. Ultra high resolution monitors will be required to make such graphics capabilities available.

Display systems are available in various technologies such as cathode ray tubes (CRTs), liquid crystal displays (LCDs), electroluminescent displays (EL), plasma displays, and light emitting diodes (LEDs). However, for high resolution monitors the CRT has been and continues to be the technology of choice. Besides its awkward shape, weight and high voltage requirements, the CRT offers many advantages over its competitors. As opposed to other display systems that require a driver for each picture element (pixel), the CRT requires a single driver to drive the tube's cathode or three drivers for a color display. CRTs also offer excellent contrast, luminance and better display resolution than its counterparts. Even though the brightness of the CRT's screen is not uniform across the face of the screen, the variation from the center to the corners is gradual and may be unnoticeable to most viewers. In the case of LCD or LED displays, however, a very tight brightness level matching is required among the adjacent pixels. Continued improvements over the years and declining prices have made the CRT a popular choice for high resolution monitors.

The operation of a CRT monitor is basically very simple. A heating element in a CRT heats the cathode and causes it to emit electrons which are accelerated and focused on a phosphor screen by means of high voltage grids. An image (raster) is displayed by scanning the electron beam across the screen. Since the phosphor's luminance begins to fade after a short time, the image needs to be refreshed continually. In order to eliminate flicker, most monitors refresh the screen at a 60 Hz rate.

Figure 1 shows a simplified block diagram of a color CRT monitor. The entire circuitry within the monitor can be grouped into three main categories: video signal processing and amplification, horizontal/vertical deflection and synchronizing, and power supply. As shown in *Figure 1*, a transmission line or a coaxial cable carries the video signal from the host computer to the monitor. The video signal is usually a 1 V_{PP} signal and thus requires amplification before the signal can be applied to the CRT's cathode. The amplification of the video signal is usually done in two stages. A low voltage amplifier, often called a preamplifier, amplifies the 1 V_{PP} signal to a 4–6 V_{PP} signal. In addition to amplification, the preamplifier also provides contrast and brightness control. Contrast control allows the user to vary the gain of the video amplifier. Increasing the contrast for instance increases the video signal's level and thus causes the lighter portions of the raster to be brighter than the darker portions. The result is a sharp picture with contrasting light and dark. Brightness control on the other hand allows the user to change the brightness of the raster by varying the DC offset of the video signal. Increasing brightness in effect makes both the light and dark portions of the image brighter. Most preamplifiers also provide DC restoration or black level clamping which makes the brightness control possible. This will be described later in the text.
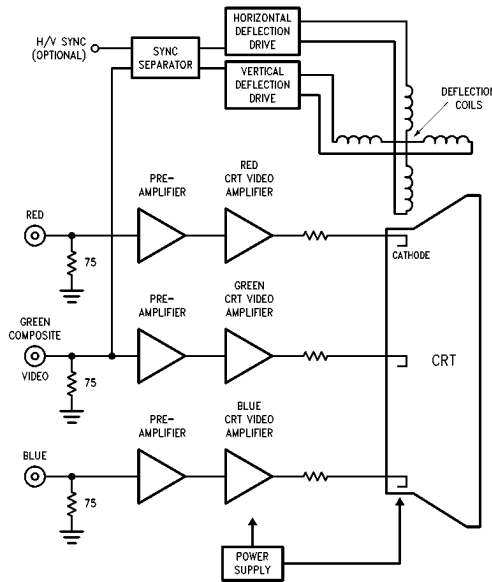

FIGURE 1. Simplified Block Diagram of an RBG Monitor

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CRT VIDEO AMPLIFIER PROVIDES HIGH VOLTAGE AMPLIFICATION

The CRT video amplifier is the second stage amplifier, it amplifies the preamplifier's 4–6 V_{PP} signal to a 40–60 V_{PP} signal that the cathode requires to energize each phosphor dot on the screen. In a color monitor, there is a trio of red, green and blue phosphor dots. Together, each trio constitutes a picture element, often called a pixel for short. The light emitted by the phosphor dot is proportional to the number of electrons striking the phosphor. Thus by modulating the voltage of each of the three cathodes in a color monitor, the corresponding phosphor dot is energized at varying intensities, thereby producing various shades of color. To change a pixel from black to peak white, the CRT video amplifier may be required to swing as much as 40 V_{PP}. The higher the display resolution of a monitor, the shorter the time available to energize each pixel. Thus high resolution monitors demand wide bandwidth amplifiers, which is generally not a problem when designing preamplifiers because of its low voltage swings of 4–6 V_{PP}. However, achieving wide bandwidth from a CRT video amplifier is no trivial task. The transistors required should not only have breakdown voltages of 70–80V but must also maintain f_T of 1 GHz to 2 GHz at high collector currents.

Table I illustrates the key requirements for various pixel display resolution monitors currently available in the market. Note that the maximum pixel time is derived assuming a 60 Hz frame refresh rate and retrace time equivalent to 30% of each frame time. Also as a rule of thumb, 33% of the pixel time is generally allocated to the rise/fall time of the signal at the CRT cathode. For ease of analysis we may assume that the CRT video amplifier is linear and has a single pole roll off. Thus the amplifier's bandwidth may be approximated as $f_{-3\,dB} = (0.35)/t_r$, where t_r is the signal rise time.

Figure 2(a) shows a simplified cross-sectional view of a color CRT. A heating element biased at approximately 6V and 500 mA to 2A (depending on the tube) heats up the cathodes. Heating the cathodes energizes the electrons in the cathodes and greatly aids in the emission of electrons. A large DC potential, on the order of several hundred volts more positive than the cathode is applied at the second grid, G2. This causes the electron beam to be accelerated towards the screen. Since the beam emerging from the cathode tends to diverge, a negative potential with respect to the cathode is applied at grid G1. By making G1 (also called control grid) more negative than the cathode, the electron beam begins to converge as shown in *Figure 2(b)*. This action is similar to beam focusing using an optical lense. Furthermore, by modulating the potential difference between the cathode and the control grid, the beam intensity and hence the brightness level is modulated. Finally the beam is electrostatically focused on the screen by adjusting grid G3's potential until the desired focus is achieved.

TABLE I

Display Resolution	Maximum Pixel Time	Minimum Pixel Clock Frequency	Required Rise Time at CRT Cathode	Required System Bandwidth ($f_{-3\,dB}$)
320 x 200	182 ns	5 MHz	60 ns	6 MHz
640 x 350	52 ns	19 MHz	17 ns	20 MHz
640 x 480	38 ns	26 MHz	12.5 ns	28 MHz
800 x 560	26 ns	38 MHz	8.6 ns	41 MHz
1024 x 900	12.6 ns	80 MHz	4.2 ns	84 MHz
1024 x 1024	11 ns	90 MHz	3.7 ns	95 MHz
1280 x 1024	8.9 ns	112 MHz	2.9 ns	120 MHz
1664 x 1200	5.8 ns	170 MHz	1.9 ns	180 MHz
2048 x 2048	2.8 ns	360 MHz	1 ns	380 MHz
4096 x 3300	860 ps	1.2 GHz	280 ps	1.23 GHz

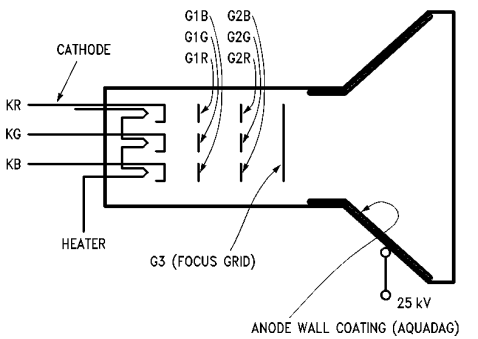**Note:** This table assumes 60 Hz refresh rate and retrace time equivalent to 30% of each frame time.

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FIGURE 2(a). A cross-sectional view of a color tube shows the arrangement of the grids.
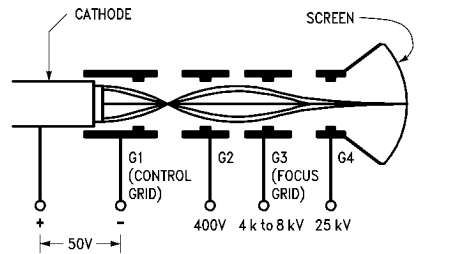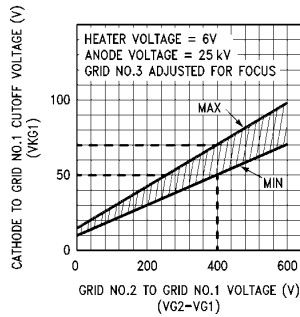

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FIGURE 2(b). The electron beam is accelerated and electrostatically focused by applying the appropriate potential at the respective grids.

COLOR TUBES REQUIRE ADJUSTMENTS
TO BALANCE THE GUNS

As the cathode potential is increased with respect to G1, a potential is reached at which the beam spot on the screen disappears. This potential is called the spot cutoff voltage and thus corresponds to the voltage that produces the black level. The cutoff voltage is usually different for each of the three guns in a color tube. Thus the cutoff voltage needs to be individually adjusted for each gun so that at cutoff all three guns are at the black level. For a picture tube of the type shown in *Figure 2*, the adjustment can be made by individually adjusting the potential at the corresponding control grid, G1. However, most modern day color tubes uses a unitized gun in which G1 and G2 are common to all three guns. Among the advantages of a unitized gun are that it produces a better spot size resulting in bright pictures and better gray scale tracking. Cutoff voltage adjustment in a unitized gun now requires that the cathode voltages be adjusted. This places a burden on the CRT video amplifier because the large variation of cutoff voltages within the tube must now be compensated by adjusting the video amplifier's DC offset. The spot cutoff design curves for a typical unitized tube is shown in *Figure 3*. At grid 2 to grid 1 voltage ($V_{G2}-V_{G1}$) of 400V the cathode to grid 1 cutoff voltage varies from 50V to 70V as shown by the curves. Thus if the CRT video amplifiers are coupled directly to the cathodes and with $V_{G1} = 0V$, the amplifiers must be designed to be able to swing at least as high as 70V because of the 20V variation between the guns within the tube. Note that biasing G2 at a higher potential would be desirable because of
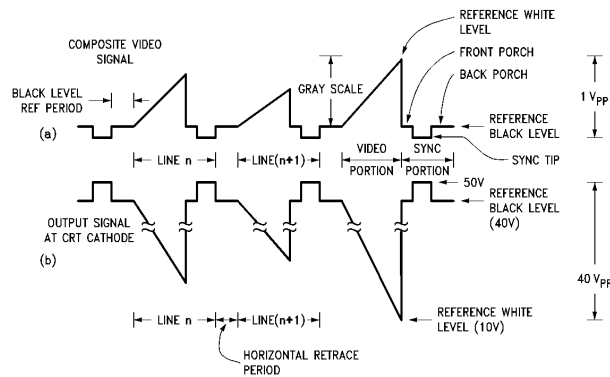
the improved spot size, consequently a brighter picture. However, doing so would require a higher cutoff voltage and thus place a heavier burden on the amplifier driving the cathode. In contrast, a monochrome CRT doesn't have this problem because of the single gun.

Neutral white is the most difficult color to produce in a color monitor because the light emitting efficiency of R, G and B phosphors is different. Thus a specific proportion of R, G and B drive levels are required at the three cathodes to produce neutral white. The peak amplitude of the cathode drive signal determines the shade of white that will be displayed. Thus neutral white is produced by adjusting the AC gain of each of the three preamplifiers. Usually the red gun is driven at maximum gain because of red phosphors's lowest efficiency, and, the gain of the green and blue guns are reduced until the desired balance is achieved. Keep in mind that once the gain adjustments have been made, the contrast control will vary the gain of all three guns simultaneously. Also the color on the screen should not change as the screen's brightness level is changed, this is often referred to as gray scale tracking. Good gray scale tracking requires that the amplifiers have good differential gain characteristics as well as good DC output tracking capability. Furthermore, the amplifiers should also track well over a wide range of contrast adjustment.

Manufacturers of computers and monitors generally follow the EIA standard RS-343 for video signal. The RS-343 standard specifies the various video signal levels relative to a reference level. It is interesting to note that no DC component is specified, the reason is that the standard was developed for television. Since the video signal in broadcast television travels through air, the DC component of the signal is lost. At the receiving end the signal is AC coupled. However, a DC restoration circuit is required to reinsert the DC component of the video signal. By reinserting the DC component of the video signal, brightness of each line is restored since the brightness may be different for each line. DC restoration is thus essential for producing the correct background illumination or shading. Likewise for monitors, the video signal is AC coupled at the input so that the monitor can easily interface with computers from various manufacturers.

Figure 4a shows the 1 V_{PP} composite video signal with sync tip. The signal at the cathode is an amplified signal of opposite phase as shown in *Figure 4b*. The video signal for three

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**FIGURE 3. Spot Cutoff Characteristics
for a Typical Color Tube**

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**FIGURE 4. The composite video signal is a 1 V_{PP} signal that carries both the amplitude and
sync information (a). A wide bandwidth inverting amplifier amplifies the signal at the cathode (b).**

lines of the raster are shown. Since the video signal is amplitude modulated, the signal's amplitude relative to the reference black level specifies the relative DC component of each line on the raster. The DC component of the video signal is thus restored by clamping the black level at a fixed reference potential (e.g., 40V), corresponding to the CRT's beam cutoff voltage. The video signal's video portion contains the gray scale information (i.e., the signal's amplitude) whereas the sync portion contains the timing information required for horizontal and vertical synchronization.

DC restoration of the video signal can be done in two ways. The first method is to use a simple diode clamp to clamp the signal at the reference black level. Diode clamping can be done either at the AC coupled input of the preamplifier or at the AC coupled output of the CRT video amplifier. The disadvantage of diode clamping is that the black level is sensitive to fluctuations in the power supply as well as noise coupling and temperature drift of the diode's forward drop. A more effective approach for DC restoration is to do a dynamic black level clamping at the back porch of each video signal. This requires the use of comparator within the feedback loop of the CRT video amplifier and the preamplifier. During the horizontal retrace period, the comparator compares the DC feedback taken from the CRT video amplifier's output with the voltage set by the brightness control potentiometer. Depending on the CRT video amplifier's output voltage, a clamping capacitor at the output of the comparator is either charged or discharged so that the feedback loop is stabilized and the video signal is restored to the black level. During the video portion of the signal, the comparator is disabled and the clamping capacitor holds the black level reference voltage until it is refreshed at the beginning of the next line. The beginning of each new line always starts from a fixed reference black level and the DC component of each line is restored. This approach not only offers excellent power supply rejection but also there is minimal black level drift because the black level is brought back to the correct reference potential during each horizontal retrace period.

WITHOUT DEFLECTION CIRCUITRY THERE WOULD BE NO RASTER

An image is displayed in a CRT by scanning the electron beam across the face of the screen. The beam is scanned from left to right on each line, moreover, at the end of each line the beam drops down to the beginning of the next line. The motion from right to left is called horizontal retrace. During the horizontal retrace interval the electron gun is biased at a potential such that the retrace lines are invisible. Note that the horizontal retrace interval coincides with the horizontal blanking interval (part of the composite signal's sync portion). There are two methods of accomplishing blanking. The first approach is to disable the preamplifier during the blanking interval and bias the CRT video amplifier at a potential higher than the CRT's spot cutoff voltage. This effectively prevents the retrace lines from being visible. The second approach involves the application of a large negative potential at the control grid (G1) during the blanking interval.

Once all lines on the screen are traced, the beam moves from the bottom to the top during the vertical retrace interval. The composite video signal contains the horizontal sync pulse which is repeated at the horizontal scan rate. The horizontal scan rate may be anywhere from 15 kHz to 240 kHz depending on the resolution of the monitor. The vertical sync pulse is much wider than the horizontal sync pulse and occurs at the end of the raster, i.e., after all lines in the frame have been traced. The vertical sync pulse is repeated at a 60 Hz rate. For proper operation, a sync separator separates the horizontal and vertical sync pulses from the composite video signals.

The simplified block diagram of *Figure 5* shows the circuitry required for horizontal and vertical scanning, also shown is a high voltage flyback power supply. The composite video signal is AC coupled to the input of the sync amplifier Q1, whose gain is determined by the ratio of its collector and emitter resistors. The inverted video signal appears at the collector of Q1 and is buffered by the emitter follower Q2. Q3 is essentially a saturating sync switch that removes the signals' video portion and leaves only the sync pulses. Resistors R8 and R9 bias Q3's base at a potential below the cutin voltage of the transistor so that Q3 is normally off. When the composite video signal's level is between the blanking level and the sync tip, Q3 saturates and produces a negative going pulse at Q3's collector. The buffered output of Q4 is a composite sync signal that contains both the horizontal and vertical sync pulses. A two stage RC low pass filter separates the 60 Hz vertical sync pulses from the composite signal.

The vertical sync pulses trigger the vertical oscillator so that the oscillator is locked at 60 Hz. The vertical oscillator is usually a relaxation oscillator and drives the power transistor Q5 with a 60 Hz sawtooth voltage waveform. Q5 in turn energizes the vertical deflection coils with a 60 Hz sawtooth current ramp. The linear current ramp produces a magnetic field in the vertical deflection coil and causes the electron beam to move from top to bottom at a uniform speed. This accomplishes the task of moving the beam progressively from one line to the next as the raster is scanned. During the vertical retrace interval there is a rapid decrease in Q5's collector current, causing the beam to retrace rapidly from the bottom of the raster to the top. The amplitude of the current ramp is usually made adjustable because this allows the user to adjust the height of the raster.

The horizontal sweep circuit works similar to the vertical sweep circuit, however, there are some major differences. Since the horizontal sync pulses are narrow and operate at high frequency, they are susceptible to noise impulses. In order to maintain trouble free synchronization, an automatic frequency control (AFC) circuit is used. Moreover, the horizontal oscillator is a voltage controlled oscillator (VCO) as opposed to the triggered relaxation oscillator for the vertical sweep circuit. The AFC compares the phase of the horizontal sync signal with that of a sample of the horizontal output signal and produces a DC correction voltage proportional to the phasing of the two signals. The AFC's output signal is an error signal that locks the VCO such that the sync signal and the horizontal output signal are maintained at the sync signal's frequency. Without horizontal synchronization, the picture would tear up diagonally. Finally, a power output transistor, Q6, drives the horizontal deflection coils with several hundred milliamps of current depending on the mA/inch deflection ratings of the tube.
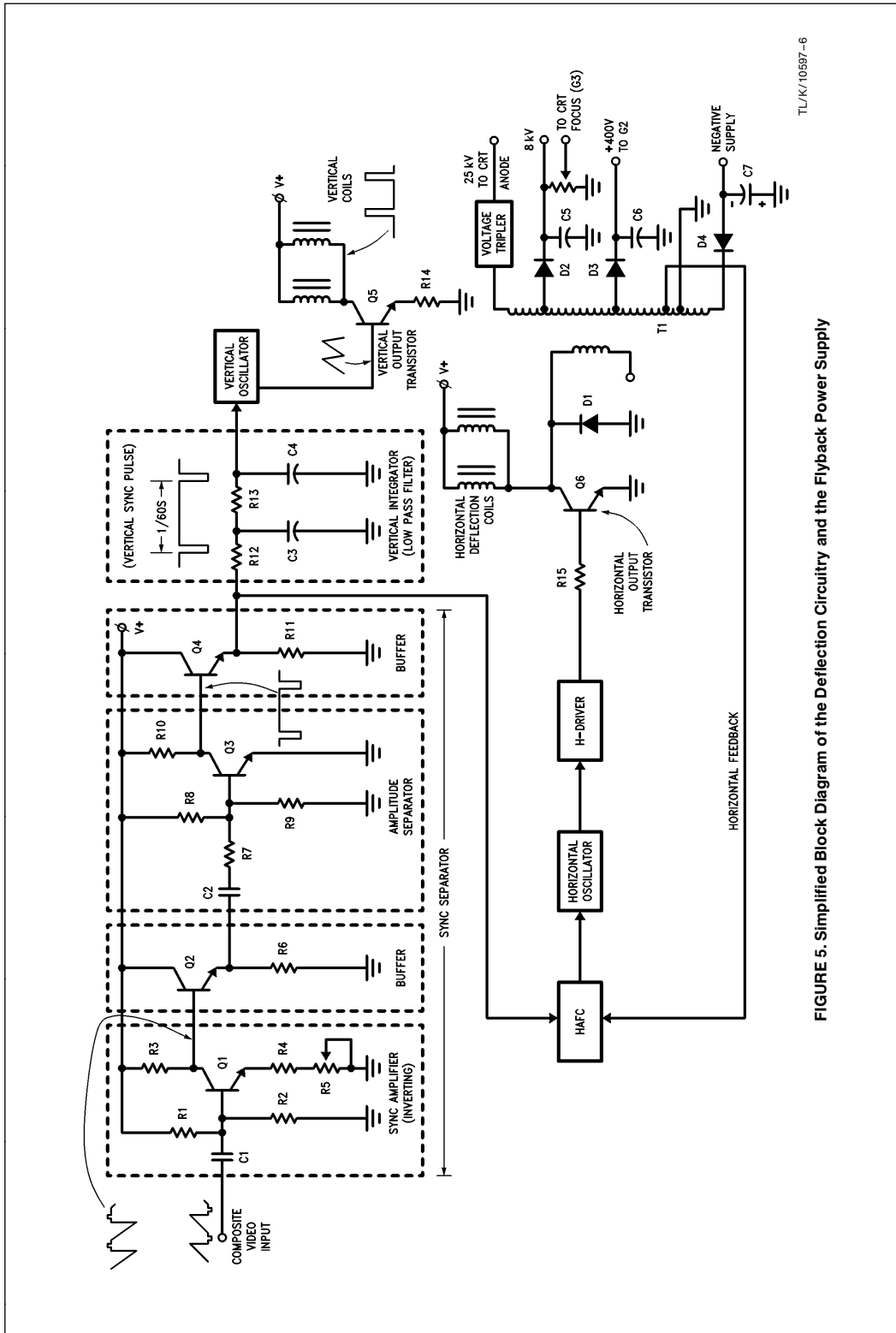
FIGURE 5. Simplified Block Diagram of the Deflection Circuitry and the Flyback Power Supply

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THE SWEEP CIRCUIT ALSO GENERATES HIGH VOLTAGES

A switching regulator is used to produce a regulated DC voltage to power the low voltage circuits and the horizontal/vertical scanning circuit. The high voltages required for the CRT's grids and the high voltage anode are derived by transformer action. The horizontal output transistor Q6 not only drives the horizontal deflection coils but it also drives the primary of the step up transformer T1.

During the horizontal retrace interval, the collector current of Q6 drops rapidly causing the transformer's magnetic field to collapse. The transformer's primary coil in turn produces a back EMF to sustain the current thus raising Q6's collector to a high potential. Through the transformer action, T1's secondary coil produces high voltages. A voltage multiplier circuit consisting of a diode and capacitor network multiplies the secondary coil's voltage to a 25,000V potential that the tube's high voltage anode requires. Other high voltages are derived by tapping various points on the secondary coil. A diode and capacitor network is used to rectify and filter the power supply voltage. A power supply of this type is often called a scanning or flyback voltage supply because of its association with the horizontal sweep circuit.

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