STORAGE CATHODE-RAY TUBES AND CIRCUITS

BY

CHUCK DeVERE

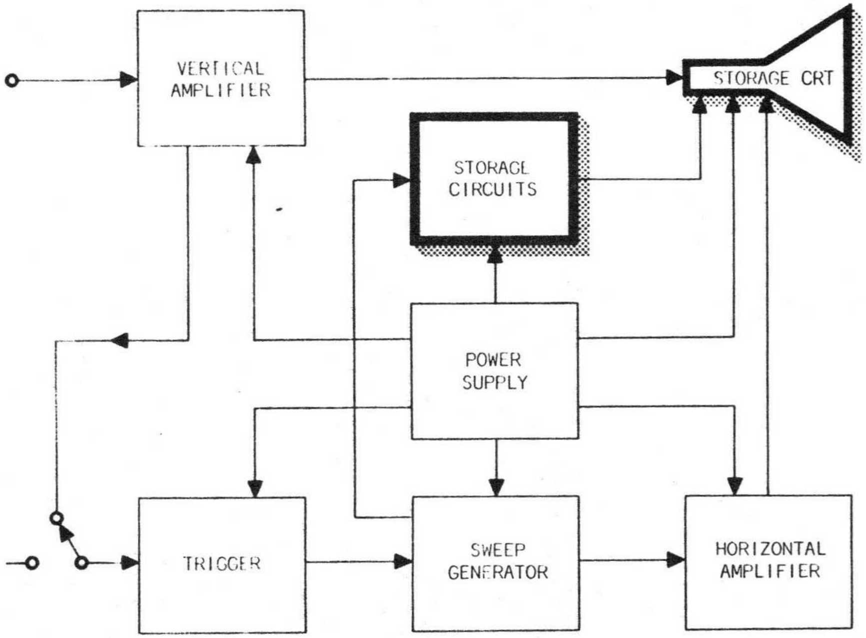
Significant Contributions
by
BOB ORWILER

CIRCUIT CONCEPTS

SECOND EDITION, FIFTH PRINTING APRIL 1971
062-0861-01

BEAVERTON, OREGON 97005

CONTENTS


VERTICAL AMPLIFIER
STORAGE CRT
STORAGE CIRCUITS
POWER SUPPLY
TRIGGER
SWEEP GENERATOR
HORIZONTAL AMPLIFIER

1

INTRODUCTION

An electrical event that occurs only once can be displayed on a conventional cathode-ray tube but the display is present only for a short period of time. This time may range from a few microseconds to sever seconds. A storage cathode-ray tube allows a displa to be retained for much longer periods of time (up t an hour or more).

The retention feature of a storage CRT is useful when displaying signals which occur only once or have low repetition rates. In the past many single-shot events required that the display be photographe Storage offers a convenient alternative. Signals having low repetition rates often cause a flickering of the display which is distracting. Storage allows these signals to be displayed at a constant light level.

Storage cathode-ray tubes may be classified as eith bistable or halftone tubes. The stored display on bistable tube has one level of brightness. A halft tube has the capacity of displaying a stored signal different levels of brightness. The brightness of halftone tube is dependent on beam current and the time the beam remains on a particular storage eleme A bistable tube, as the name implies, will either store or not store an event. All stored events hav the same brightness.

Storage cathode-ray tubes may also be classified as either direct-viewing or electrical-readout type tu An electrical-readout type tube has an electrical input and output. A direct-viewing type tube has a electrical input but a visual output.

This book deals primarily with direct-viewing bistable storage tubes and associated circuit concepts. Basic direct-viewing storage tube principles develop in a step-by-step manner from a simple model to a functioning tube. Also covered: the characteristics of bistable tubes and associated typical circuitry.

2

BASIC PRINCIPLES OF DIRECT-VIEWING STORAGE TUBES

storage target

bombarding energy

A *storage target* is a surface having the ability to store information when bombarded by an electron bea One of the key questions in analyzing storage target behavior is how much bombarding energy a beam of electrons has as it arrives at the storage target surface. The bombarding energy of an electron on a target is directly related to the potential differe between the voltage of the target and the voltage o the electron's source (usually a thermionic cathode Consider Fig. 2-1 which shows a cathode, two accelerators, a decelerator and a target. Electron are emitted from the heated cathode at zero volts, accelerated to +1000 V, decelerated to +500 V, accelerated to +3000 V and then bombard a target wh voltage is +200 V. The electron potential at the target is *+200 V*, because the high-speed electrons the +3000 V field must pass through a decelerating field immediately surrounding the target.

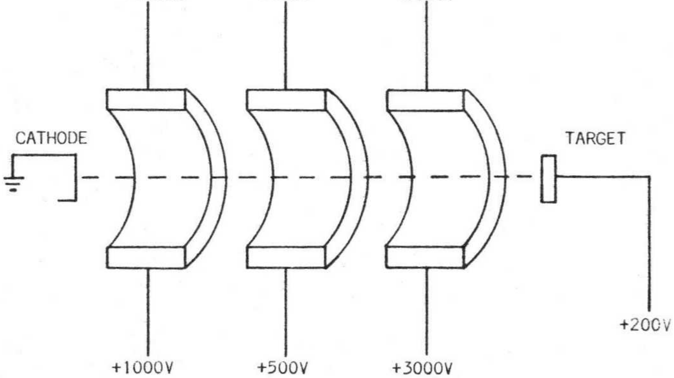


Fig. 2-1. Electron energy at the target is equal target voltage - cathode voltage.

This idea is emphasized at the outset, because more complex situations involving this principle will be discussed later. Remember, it is not necessary to know the whole history of an electron along its entire path in order to know its bombarding energy. If the voltage of the emitting source and the target is known, the electron potential can only be equal to the voltage difference.

electron
potential

ELECTRON POTENTIAL = TARGET VOLTAGE - CATHODE VOLTAGE

The above formula implies that an electron emitted from a cathode at zero volts would have zero potential on arriving at a target held at zero volts. The assumption has been made that electrons emitted from a hot cathode have no initial velocity. It has been found that electrons emitted from *any* source (thermionic cathode, photoemission, field emission, and secondary emission) have an energy of emission associated with them. Electrons emitted from a thermionic cathode will have a range of energies which can be measured by the retarding potential required to repel the electrons. A target with a voltage of -0.01 volts will repel only about 10% of the electrons emitted from a hot cathode at 850°C at zero volts. When the target voltage is -0.1 volts, about 66% of the electrons are repelled and when the target is at -1 volts, about 99% of the electrons are repelled.

stopping
potential

The potential required to repel substantially all of the electrons from a particular cathode in a particular tube is often referred to as the *stopping potential* for that tube. The idea of stopping potential is useful later to explain why the region between complete collection and substantial repulsion of emitted electrons by a target is a rounded curve rather than a sharp cutoff.

secondary
emission

Most storage tubes use the phenomenon of secondary electron emission to build up and store electrostatic charges on the surface of an insulated target. An understanding of this concept is imperative to the understanding of storage tubes.

When a target surface is bombarded by electrons, some of the energy of the bombarding or *primary* electrons separate other electrons known as secondary electrons from the surface of the target. The number of secondary electrons emitted depends on the number and velocity of the bombarding or primary electrons, the target composition, surface condition, and the angle of bombardment. The amount of secondary emission is usually expressed as the ratio of secondary-emission current (number of electrons per unit time) to the primary beam current and is termed the secondary-emission ratio or δ (delta).

secondary-emission ratio

$$\text{Secondary-Emission Ratio, } \delta = \frac{\text{Secondary-Emission Current, } I_s}{\text{Primary Beam Current, } I_p}$$

An elementary but fundamental experiment with this effect is the determination of how the secondary-emission ratio changes when the bombarding primary electron beam energy is changed.

secondary-emission measurement

A typical experimental device for the measurement of the secondary-emission ratios of a variety of materials is shown in Fig. 2-2.

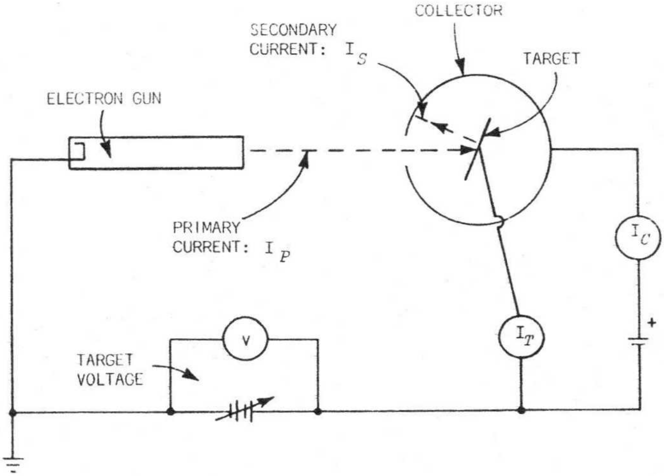


Fig. 2-2. Secondary-emission circuit for a conductive target.

The target voltage relative to the cathode determines the primary electron potential. The plot (Fig. 2-3) shows secondary-emission ratio (δ) vs target voltage.

In this experiment, a primary electron gun forms an electron beam which bombards a metal target plate in a vacuum. The target voltage is the independent variable for the curve to be plotted. A collector electrode surrounds the target, and it is held a few volts more positive than the target electrode by a voltage supply which is between the target and the collector. There will always be a strong enough field around the target electrode to insure collection of all the secondary electrons in this device.

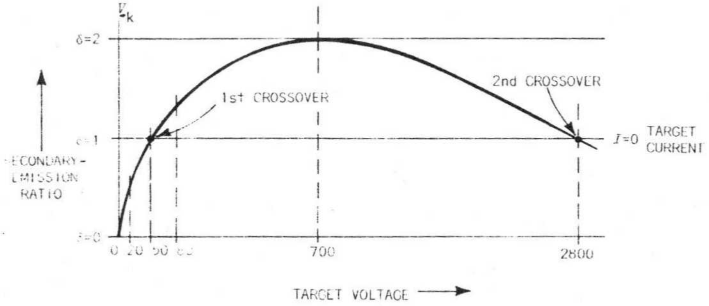


Fig. 2-3. Typical secondary-emission yield curve.

At some low positive target voltage, such as +20 volts, a primary beam current of 10 μA may cause a secondary current of perhaps 5 μA to flow from the target to the collector. The secondary-emission ratio would be 5 μA/10 μA, or 0.5. Notice that since the target is receiving 10 μA but is losing 5 μA of current by secondary emission, the net electron current collected by the target, and leaving the envelope through the target-lead wire, is only 5 μA.

At some higher target voltage, such as +50 volts, the bombarding energy is higher and the secondary current may rise to become equal to the primary-beam current. A 10 μA beam producing 10 μA of secondary-emission current from the target to the collector then results in a secondary-emission ratio of 1. Since the target is collecting 10 μA and losing 10 μA, the net flow of current in the target lead wire is zero. Conditions where the secondary-emission ratio is unity will later be seen to have a special importance. Since the secondary-emission curve crosses the ordinate lines of $\delta = 1$ at such points, these points are often called *crossover* points, and the point just described, which is *the lowest target voltage at which this crossover occurs*, is usually referred to as the *first crossover* point.

first crossover

Fig. 2-3 shows that the direction and amount of flow of current in or out of the secondary-emission target surface, and in the lead-wire to the target, depends on the secondary-emission ratio. An additional scale of ordinates has been added on the right side of the figure to show net current through the target surface. The current scale is in units such that one unit equals the total primary-beam current.

When the secondary-emission ratio is one, there is no net flow of current to or from the target, and the current in the target lead-wire is labeled $I = 0$ in the figure. The current ordinate in Fig. 2-3 is given a positive direction for current flow into the collector, since the target surface is losing negative charge or gaining positive charge.

At some higher target voltage, such as +80 volts, the 10 μA of primary current may cause 13 μA of secondary current, resulting in a secondary-emission ratio of 1.3. The net flow of current at the target surface is now away from the target, since more current is emitted than is collected. An electron current of 3 μA now flows into the collector from the target lead-wire. At a higher target voltage, such as +700 volts, the secondary-emission ratio may reach a maximum, for example at $\delta = 2$. Above this voltage, the secondary-emission ratio decreases until, at perhaps +2800 volts, the secondary-emission ratio may again equal 1. This is another crossover point of special interest, and is commonly called the *second crossover* point. The drop in secondary emission which occurs above the maximum point is believed to be the result of deeper penetration of the more energetic primary electrons into the target material, before collision with the target atoms occurs. Large numbers of secondary electrons may be produced below the surface, but many are captured within the target before they reach the surface, and do not contribute to the current leaving the target.

second crossover

constant
collector
voltage
effects

The preceding explanations have discussed the phenomena of secondary emission with the collector electrode always more positive than the target. Other electron-optical effects take place when the collector electrode voltage is held constant. These effects provide the basis for the study and understanding of bistable storage devices.

Fig. 2-4 differs from Fig. 2-2 in that the collector electrode is held at a fixed +200 V. This is the first of a series of changes to be considered in the step by step evolution of the understanding of a direct-viewing bistable storage tube.

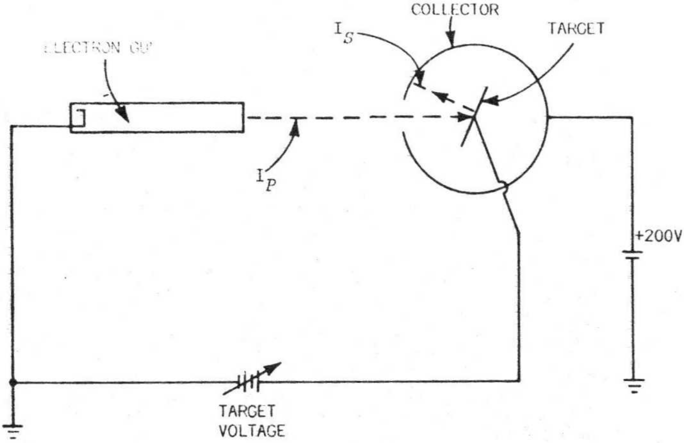


Fig. 2-4. Secondary-emission circuit modified to show effects of fixed collector voltage.

With the arrangement in Fig. 2-4, the secondary emission which occurs when the target is below +200 volts is collected as before, because the collector is more positive than the target. This emission and collection is shown on the curve of Fig. 2-5, just below the fixed collector voltage point.

When the target is well above the collector voltage, at +500 volts for example, secondary-emission electrons leave the target surface due to their energy of emission. The electrons are emitted into a retarding field caused by the lower collector voltage, which reflects most of them back to the target. Under these conditions, the net secondary-emission current is near zero, since essentially no secondary current reaches the collector. The target is receiving the primary beam current, and is acting simply as a collector of current. Current measurements from outside the envelope would show that the target current equals the primary beam current, δ = 0, and the collector current is zero.

These are also the current conditions for a target material which is such a poor emitter of secondary electrons that no substantial emission current is collected. It can be seen that current measurements in this device cannot distinguish between the total return to the target of secondary electrons by the collector, and a true secondary-emission ratio of zero.

effective secondary emission

Another important effect occurs in the vicinity of zero volts, on the curve of Fig. 2-5. This effect results in a modified "effective" secondary-emission curve.

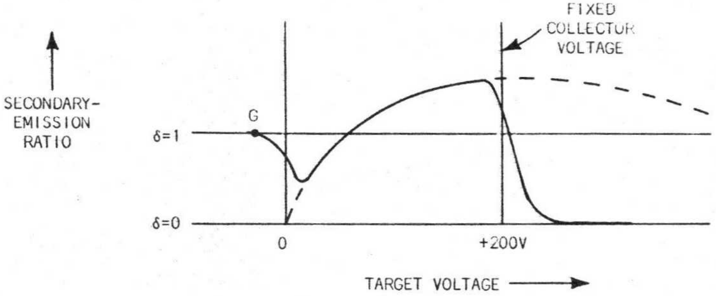


Fig. 2-5. Secondary-emission curve modified by fixed collector voltage.

At some point G which is substantially below zero volts (e.g., -5 V), the target is surrounded by a negative (repelling) field, which reflects all primary electrons to the collector. External current measurement shows that the collector current equals the primary current, and the target current is zero. These are the same current measurements which occur at the crossover points, where the secondary-emission ratio is one. At this voltage the target has an apparent or net effective secondary-emission ratio of one. The current measurements cannot distinguish between the total reflection of primary electrons, and the physical effect of a true secondary-emission ratio of unity.

As target voltage is increased, approaching zero volts from the negative side, it leaves the region of reflection of primary electrons and enters the region of actual target bombardment and true secondary emission.

The region around zero target volts is of particular interest since both halftone and bistable storage targets operate partially in this region.

apparatus effects

The results of these two "apparatus effects" is the *net* secondary-emission curve of Fig. 2-5. This is *the* important curve for bistable devices, and will be used often.

To summarize: The curve differs from the physical effect of secondary emission at both ends of the curve; near zero volts and near collector voltage. It differs for the same reason in each case; reflection of electrons by a more negative electrode. Reflection of primary electrons by the target occurs below zero volts; reflection of secondary electrons by the collector occurs above the collector voltage.

3

CHARGING AND BISTABILITY

floating target

At this point, another important change in the experimental tube will be discussed which will result in a device which is capable of simple storage effects. This effect will be accomplished by the use of a floating target instead of a target whose voltage is externally controlled.

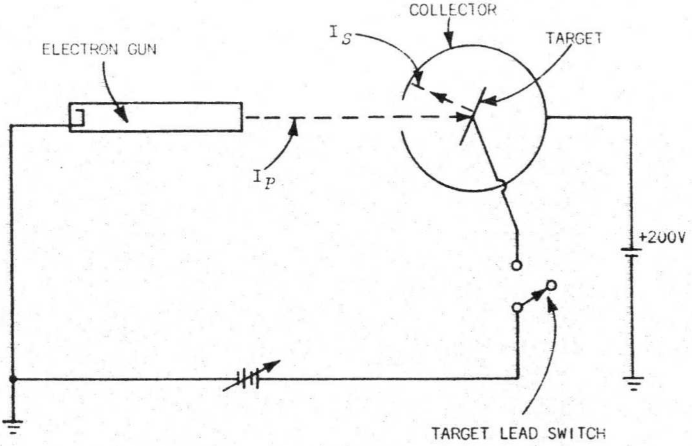


Fig. 3-1. Secondary-emission circuit modified to allow floating target.

floating target potential change

The device shown in Fig. 3-1 can be used to determine experimentally in which direction the potential on the floating target changes due to target charging, for any particular initial target voltage. With the switch closed, the target supply may be adjusted to any starting condition, and then the switch opened and the changing target voltage measured.

When the target is set at some low voltage such as +20 volts, a secondary-emission ratio of about 0.5 may typically result, as shown at point D in the curve of Fig. 3-2. For every unit of primary current collected by the target, 0.5 unit of secondary current flows back into the vacuum, so the net collection effect is 0.5 unit of electron current, which flows out of the envelope on the larget lead-in wire.

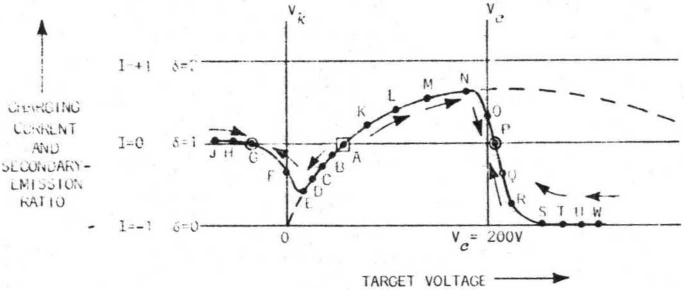


Fig. 3-2. Secondary-emission curve - fixed collector voltage.

If the switch in the target lead is now opened, the current in the target lead-in wire is interrupted, and the target starts to charge in a negative direction, due to the net collection of electrons. The target voltage then shifts downward from point D.

The curve of Fig. 3-2 is the result of opening the switch in the target circuit at many different target voltages, to determine its charge direction as a function of target voltage, as shown by the direction of the arrows. As the target charges more negative from point D, its voltage decreases sequentially to the voltage at points E, F, and G on the curve. The secondary-emission ratio changes as the target voltage changes, but it remains below one, between points A and G, so the direction of target charging remains negative, although the charging rate varies.

The rate of charging decreases as the target voltage closely approaches voltage G, since the secondary-emission ratio approaches 1. When the target reaches point G, the net charging rate becomes zero and there [illegible] further drop in target voltage.

If the target circuit is opened when the target is between point G and J there is no net charging by secondary emission. Positive ion bombardment and conductivity across the insulating target support structure will cause the target to charge slowly in a positive direction, until point G is reached. The curve above point J shows that this effect results in a positive direction of charge, just as if the secondary-emission ratio were greater than one.

A target's voltage becomes *stable* when it arrives at point G. The charging effects balance to zero at this point, whether the target has been dropping in voltage from a higher voltage or charging positive from a lower voltage.

erase

lower
stable
point

If a target at point G is temporarily disturbed from its rest position by a small voltage shift, in either direction, the net charging effect is no longer zero. A charge arises having a direction which restores the target to the voltage of point G. Since there is a restoring force on a target in the vicinity of point G, this point is a stable point as long as the primary electron beam is present to preserve this stability. A target at this point on the curve is referred to as being erased or unwritten. To "erase" a target in this device means to change the voltage to the lower stable point of the curve.

write

upper
stable
point

The curve segment P-W has a net charging direction which is negative over the whole segment. When the target circuit is opened at the voltage of point W, for example, the target charges in a negative direction toward point P because $\delta<1$. As point P is approached, the charging ratio decreases because the secondary-emission ratio is approaching one, and the net target current is approaching zero. At point P, the target voltage stops dropping and becomes stable, the net charging rate is zero because $\delta = 1$. A target at this point on the curve is referred to as being "written." To "write" a target in this device means to change its voltage to the upper stable point on the curve.

The segment A-P of the curve lies entirely above a secondary-emission ratio of unity, so at every point on the segment, the net current is away from the target. This loss of negative charge drives the target more positive. When the switch is open, a target at point K increases in voltage until it reaches the voltage of point P, the rate of charge dropping to zero as it approaches.

When a target has charged to the voltage of point P, either from a higher or lower voltage, it has reached a voltage which is stable. A small disturbance of the target voltage will be corrected by restoring forces that return the voltage to point P, *as long as the primary beam is present to preserve stability.*

stable points

Notice that at the two stable points G and P, the curve of Fig. 3-2 crosses the line I = 0 with a negative slope. A stable point in a floating target voltage occurs wherever the curve of net charging current crosses I = 0 with a negative slope.

unstable point

At point A, the net charging current is also zero, but a small change in target charge from any "noise" source will send the target charging up or down to point P or G, depending on which way the voltage is first shifted by noise. Point A is a uniquely unstable point, and it should be noted that an unstable point in the voltage of a floating target occurs wherever the curve of net target charging current crosses I = 0 with a positive slope.

Since the target now has two stable points, G and P, at which its voltage will be held by restoring forces, (which point depends on its history before the switch in the target circuit was opened) we see that this device is an elementary bistable storage tube. This tube may be interrogated by measuring the target voltage. The measurement will tell whether the voltage supply was above or below the voltage of point A at the time that the switch was opened. The information is present in the form of a voltage at the target lead-wire, but there is no image displayed. This tube is an electrical readout tube (of one-bit capacity) as opposed to a direct-viewing storage tube. Bistable storage is frequently referred to as having "infinite" persistence, since the tube will retain its stored information indefinitely.

mechanical stability model

Stability is dependent on the presence of a restoring force. This fundamental idea can be made more familiar by comparison to a mechanical model. Fig. 3-3 shows a shaped surface with a small ball resting on it, under the influence of gravity. The ball will remain indefinitely in either of the stable positions G or P, if once placed in either of these positions. These sections of the model are comparable to the stability of the storage target just described, which will remain at either of its two stable voltages indefinitely.

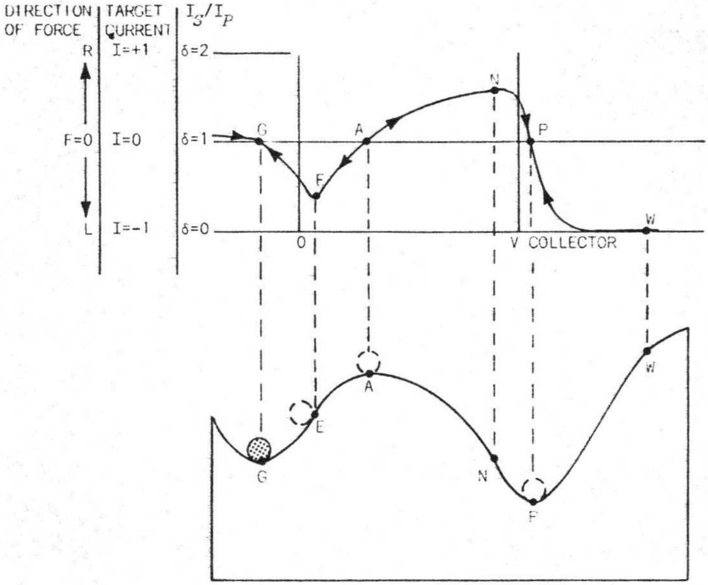


Fig. 3-3. Mechanical stability model and secondary-emission curve.

If the ball at point G is displaced to the right, to point E, it experiences a strong restoring force which returns it to point G; in fact, the surface at point E is the steepest slope on this portion of the model. This section of the model is comparable to a target at point E which is restored to stable point G, and has the highest negative charging rate on this part of the curve, at point E, where the effective secondary-emission ratio is low.

If the ball is placed at point A on the mechanical model it is unstable, and will drop to point G or P at the slightest disturbance, just as a target at point A on its curve is unstable and will shift to G or P at the slightest disturbance.

Notice that points E, N, and W on the target charging curve are points of highest charging rate, and correspond to points of maximum slope on the mechanical model. Points G, A, and P have zero charging rate on the charging curve and zero slope on the model.

The slope of the surface of the mechanical model is such that a graph of the forces on the ball at any point on the model's surface has the shape of the δ curve. The graph and the arrows on it show the amount of force on the ball, and the direction of force, which is to the left where the curve is below the line $F = 0$. An ordinate scale may be added on the left side of the graph showing this force. This one graph now shows effective secondary-emission ratio of a target, the amount and direction of target charging, the amount and direction of force on the ball, and the stable points for both the ball and the target.

Important Note--

-- The text to this point is applicable to storage cathode-ray tubes in general. The material on the next few pages should not be interpreted as necessarily applying to Tektronix storage tubes but as part of the historical evolution of storage CRT's. After the evolution of storage in general is completed, the construction characteristics and operation of Tektronix storage tubes is covered starting with Chapter 5.

It is possible to change the voltage of a target in either direction by shifting the cathode voltage of a single bombarding electron gun, to obtain a high-energy or low-energy beam at the target. Either a high or low secondary-emission ratio can be obtained, making the target charge up or down to the opposite stable point. In practical storage tubes, however, the cathode of a primary beam is generally not shifted in voltage, because the bias, focus, anode, and deflection voltages would all have to be shifted with it to maintain the beam size, location and current. It has been found much more practical to use two guns having their cathodes fixed at different voltages, and to keep most of the gun electrodes at fixed voltages.

Target
control
with two

Accordingly, a step in the series of modifications of the previous simple devices, evolving toward the complete storage tube, can now be made. The next change will be to add a second electron gun, providing a second beam of primary electrons.

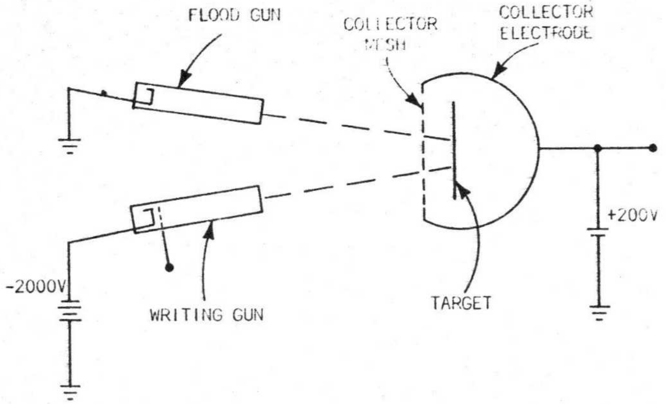


Fig. 3-4. Floating target control with two guns.

mesh

In the tube of Fig. 3-4, the entrance aperture in the collector has been enlarged to admit two electron beams. The resulting reduction of the strong collecting field in front of the target has been corrected by placing a mesh across the entrance aperture. The mesh maintains substantially the same field that would be there if a solid part of the collector occupied that position. A transparent high-transmission mesh is used for this purpose, to pass most of the primary electrons.

flood gun

writing gun

The upper gun will be called the *flood gun* and the lower gun the *writing gun*, in anticipation of later usage. For the present, the distinguishing feature of the flood gun is that it will flood the target at all times, not just intermittently as the writing gun does. Assume for the moment that the lower gun, the writing gun, has been biased to cut off, and is not bombarding the target. The tube cannot be written or erased by an external target voltage supply, because there is no connection to the floating target. This tube also cannot be written or erased with the single-gun effects of shifting cathode voltage, because we have fixed the cathode voltage instead of providing a variable voltage supply.

Since the flood-gun cathode is at zero volts, the target voltage in the charging-current curves may be read directly as the voltage difference from cathode to target. This is not the case for the writing gun, as the writing-gun cathode is fixed at -2000 volts relative to the flood-gun cathode.

writing

Writing is accomplished by gating on the writing beam with the writing-gun grid.

The combined effect of two beams hitting the same target surface is simply the sum of the individual effects that each beam would have alone. The secondary-emission ratio due to one beam is not known to be affected by the presence of a second beam having a different bombarding energy. (See Fig. 3-5.)

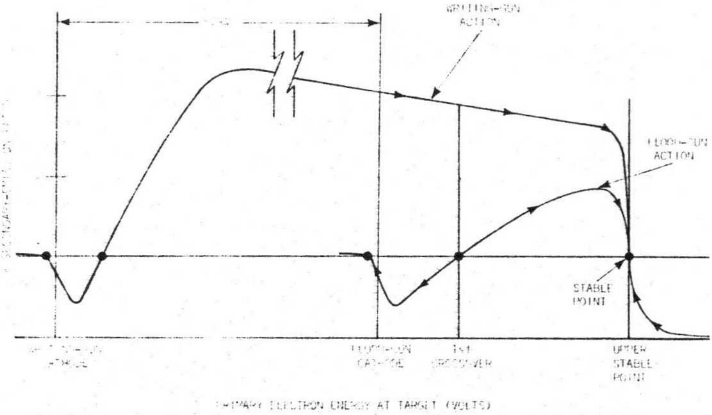


Fig. 3-5. Secondary emission.

When the target is at its lower stable point and the writing gun is gated on, electrons arrive at the target with a potential of about +2000 volts. The high secondary-emission ratio of the target for +2000 volts causes a high positive charging rate and the target voltage immediately starts to increase. As the target voltage leaves the lower stable point, restoring forces begin to oppose the writing effect of the writing gun, due to the stabilizing effect of the flood gun.

target charging

If the effect of the writing-gun current is greater than the effect of the flood-gun current, the target will charge up to the first crossover point and higher. After the target voltage exceeds the first crossover point for flood-gun emission, the flood gun is no longer opposing the writing effect, but is aiding it. It is only necessary for the writing gun to be gated on long enough to carry the target just past the first crossover. Flood currents alone will carry the target the rest of the way to the upper stable point. When the writing-gun beam is gated on for too short a period to carry the target past first crossover, the flood beam will return the target to the lower stable point after the writing beam is biased off, and storage will not occur.

During writing, the target shifts over the range from the lower stable point, slightly below zero volts, to the upper stable point, at about +200 volts. The writing-beam potential shifts from +2000 volts to +2200 volts because of the target voltage change.

This represents a little change in secondary-emission ratio for the writing beam, and, for any particular beam current, we may regard the writing beam as a nearly constant source of positive charge (via loss of secondaries) being delivered to the target, which overcomes the stabilizing current due to the flood gun.

erasing

The above explains how writing and storing are accomplished without shifting cathode voltages, by using two guns. Restoring the target to the lower stable point is carried out by pulsing the collector negative.

negative target charging

If it is assumed that the capacitance from the collector to the target is at least equal to the capacitance from the target to all other electrodes (which is a very conservative assumption in this tube), then half of the collector voltage change appears on the target. If the collector voltage is suddenly dropped by 150 volts, from +200 volts to the first crossover point at about +50 volts, two effects occur which tend to charge the target negative. One of these is the capacitive coupling of the collector signal to the target, which immediately drops the target voltage by 75 volts (in this example) to a new target voltage of +125 volts. The other effect is the negative charging of the target by primary collection. The collector cannot collect secondaries from the target when the collector is far more negative than the target, so, the secondaries are reflected back to the target, the effective secondary-emission ratio is below one, and the target collects flood-gun primaries and charges negative. This continues until the target reaches the lower stable point just below 0 volts.

The collector cannot now be suddenly returned to +200 volts without changing the target voltage, because the target would be pulled above the first crossover by capacitive coupling, and be written again by the flood beam. Instead, the collector may be returned to its voltage of +200, if desired, by a series of steps of voltage, each step small enough so that the target is not driven above first crossover, and each step followed by a delay long enough for the target to charge back down to the lower stable point from which it was displaced by capacitive coupling. A more practical method is to raise the collector voltage continuously, but at a rate slow enough that the negative-charging restoring forces on the target, near the lower stable point, are able to overcome the capacitively coupled positive charging effect enough to keep the target below first crossover and that the target doesn't charge positive to the upper stable point. A typical erase waveform that could be applied to the collector is shown in Fig. 3-6.

erase
waveform

The recovery time needed for the collector voltage depends on the particular tube design and the flood current.

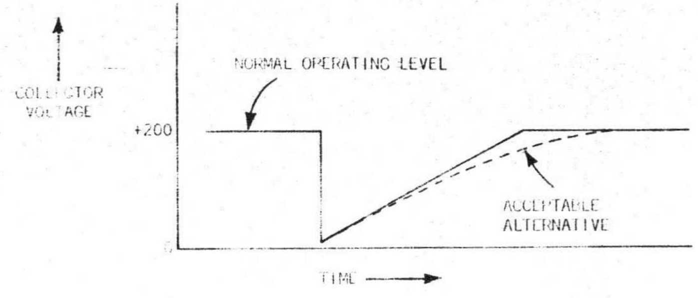


Fig. 3-6. Erase waveform for secondary-emission circuit.

It has been seen, in this section, that a floating target with no access to external supply voltages can be put in either stable position by control of the primary beam energy, or by control of the collector voltage. This is the first tube in the sequence which writes, stores, and erases a floating target with guns at fixed voltages.

4

BISTABILITY IN MULTIPLE TARGETS AND DIELECTRIC TARGETS

multiple targets

The next step in the structural evolution of a bistable storage tube (shown in Fig. 4-1) is to increase the number of targets within the tube.

In this tube, the flood-gun spot size has been very greatly enlarged to extend over all of the targets. This can be done with a relatively simple short gun, having no need for deflection plates. The writing gun still emits a focused, directed beam, and all of the writing beam current is directed toward one target at a time, such as target 3 in Fig. 4-1.

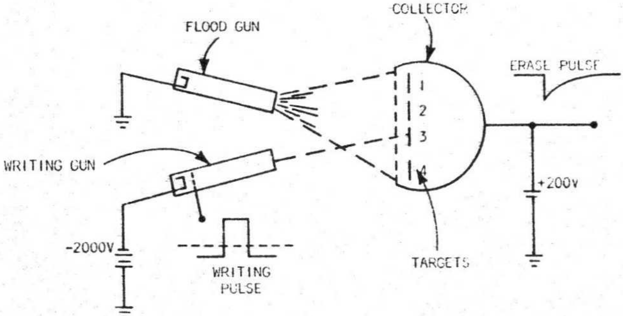


Fig. 4-1. Control of multiple targets with two guns.

Initially, the writing gun is biased off, the flood-gun cathode is grounded, the collector is fixed at +200 volts, and all targets are at their lower stable point. The restoring forces of bistability are present for all of the targets, and the flood gun is able to hold each target independently at either of its two stable points, once they are written or erased to those points.

When the writing beam is gated on and bombards target 3, for instance, this target charges positive and is written to its upper stable point. Target 3 is then held at its upper stable point, while the other targets remain held at their lower stable point by the flood gun.

When the erase pulse in Fig. 4-1 is applied to the collector, the written target is made to act as a