The development of analogue storage oscilloscopes

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Introduction

The oscilloscope is probably one of the most widespread measuring instruments in electrical and electronic engineering. Whenever the time course of electrical phenomena is to be observed, oscilloscopes are around. This range of application is even wider, if other physical quantities such as air pressure, mechanical tension or temperature are converted into electrical signals using transducers.

Traditionally, the key component of an analogue oscilloscope is the cathode ray tube (CRT). Within the CRT an electron beam, after having been electrostatically deflected and accelerated, hits a phosphoric layer deposited on de inside of the CRT-screen, creating a visible light spot. The basic configuration of an analogue oscilloscope is depicted in figure 1.

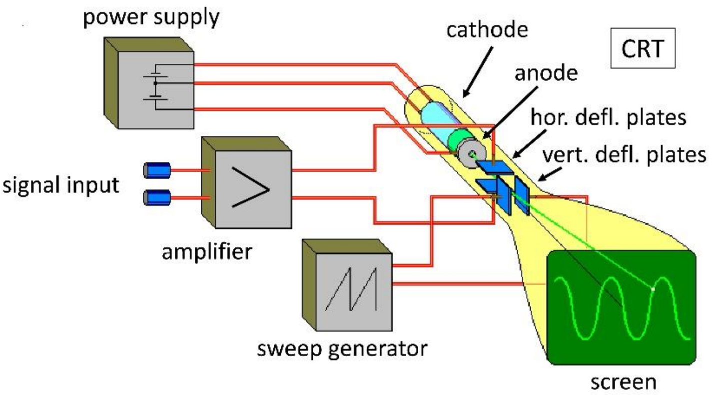

Figure 1: The basic configuration of an analogue oscilloscope

In figure 2 the inside of such an oscilloscope is shown. Note that the tube is encased in a metal housing for shielding from external magnetic fields. These fields may influence the direction and focusing of the electron beam and thus disrupt the display.

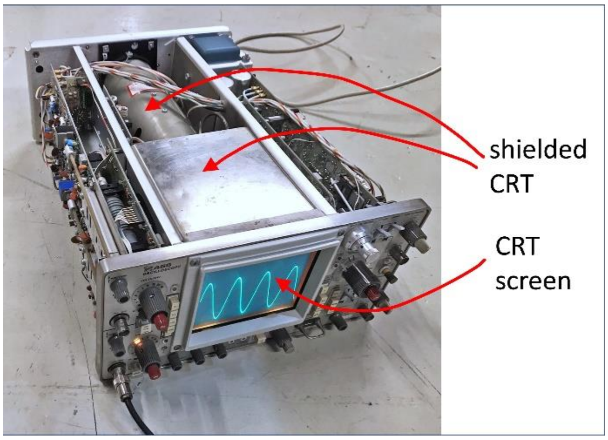

Figure 2: Interior of an oscilloscope

The intensity of the light spot depends on the energy of the electrons hitting the phosphoric particles. Furthermore, the phosphor continues to emit light a short time after the electron beam is removed: this phenomenon is known as persistence. The light intensity rapidly decays with time, the duration being dependant on the phosphoric material. If we want to observe very slowly varying phenomena, this decaying is much to fast. Also, transient type or 'single shot' phenomena are hard to observe with traditional oscilloscopes. Therefore, some form of memory is desirable. Before there were electronic memories, researchers tried to include some storage properties within the CRT. This led to the development of *storage CRT's*.

First steps in storing information using CRT's.

The development of storage CRT's can be traced back to the time when the first electronic digital computers were developed. Apart from logic circuitry, the need for memories was felt, for either storing data or instructions. We are talking about the early fifties of the last century, so there was no such thing available as semiconductors or ferrite. In 1946 it was shown by F.C. Williams, (working on the famous ENIAC-computer at the British Telecommunications Research Establishment) that a CRT indeed could be used as a (digital) memory [1]. The storage principle was based on the fact, that, if the screen of the CRT is hit by sufficiently high energy electrons, a positive charge is left at the location of impact. This is due to secondary emission as will be discussed later. Reading the memory is made possible by putting a thin metallic plate in front of the CRT-screen. The positively charged dot on the screen, separated by the CRT-glass and this metal plate form a charged capacitor. Reading out the memory is accomplished by scanning the screen with a low energy electron beam. When a charged spot on the phosphor layer is hit, a small discharge current is induced in the metal plate enabling the reading of the stored information. The position of the beam at this moment in fact represents the address of the memory. However, since, the charge persists for about 0.2 sec (depending on the phosphor used), the memory contents have to be refreshed repeatedly. The principle of repetitive reading and rewriting was also used in the Mercury Acoustic Delay Line memory and later in the solid state dynamic Random-Access Memory (RAM).

Basic principles of storage CRT's

Once the principle of storing information using a CRT was demonstrated, the development of storage CRT's for oscilloscopes began. As mentioned before, storage is based on secondary emission of electrons, which will be discussed in more detail. If electrons hit a material with sufficient energy (speed), other electrons are released from that material: these are called *secondary electrons*. If the energy of the incoming electrons is increased, the number of secondary electrons increases as well. We will refer to the material hit by the incoming electrons as the *target*. The interaction of electrons hitting a target is illustrated in figure 3.

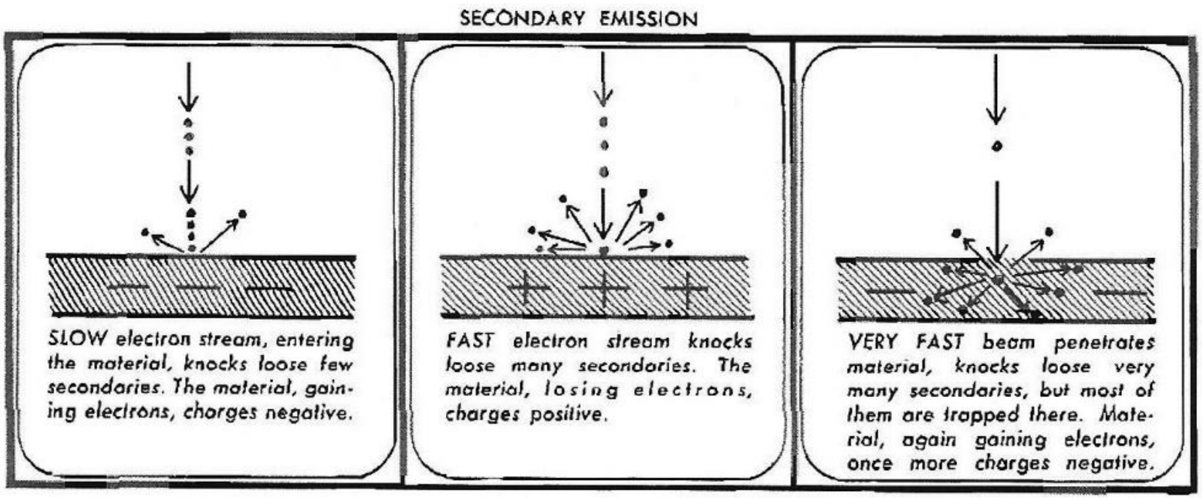

Figure3: The effect of electrons hitting a surface (figure derived from [2])

An important factor is the so-called secondary electron ratio δ, which is the quotient of the number of emitted and received electrons.

$$\delta = \frac{secondary\ emission\ current}{primary\ beam\ current}$$

In figure 4 this quotient is plotted as a function of the energy of the incoming electrons.

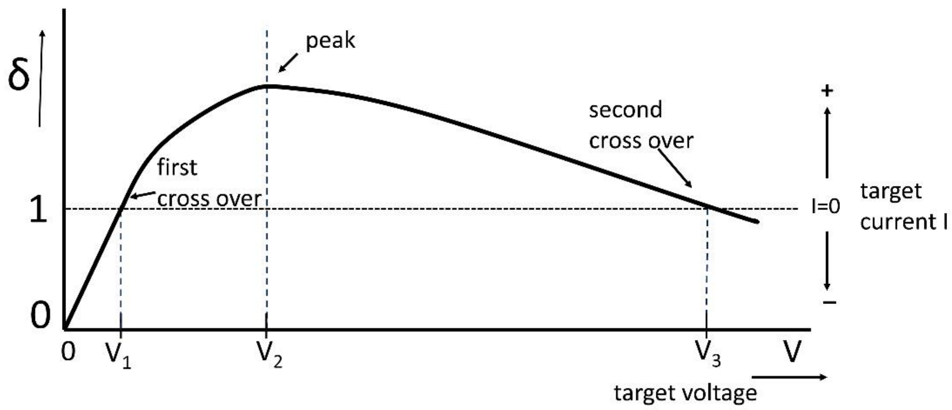

Figure 4: The secondary emission ratio as a function of the target voltage.

As can be seen, δ increases with the target voltage V. Above V_1, δ becomes greater than 1 which means that more electrons are emitted than received, hence leaving the target with a positive charge. However, as mentioned above, further increase of V (say after V_2) leads to a decrease of δ, eventually (say at V_3) leading to $\delta < 1$. His latter affect is because extremely fast electrons penetrate rather deeply into the material. Most electrons, that are released there are immediately trapped again within the material, the net result being that the target charges negative.

There are two ways of implementing a memory function in a CRT, both based on secondary emission of electrons, viz the *phosphor memory* and the *mesh memory*. Both techniques will be discussed.

The storage CRT differs from the standard CRT as shown in figure 1, in the sense that some extra elements are added.

Phosphor memory tube

In the phosphor memory tube, the screen consists of a phosphor layer and a thin transparent conducting coating, located in between the phosphor layer and the glass envelope). Two extra electrode configurations are added: the *flood guns* and the *collimator bands* (figure 5).

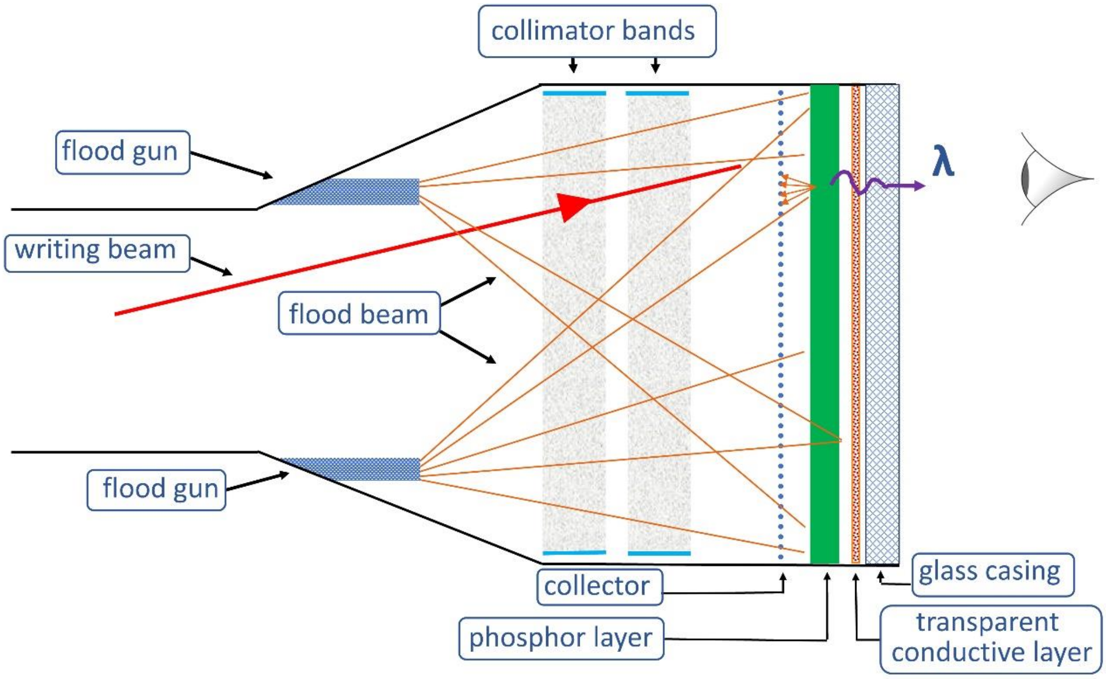

Figure 5: Lay-out of the phosphor memory CRT (Direct View Bistable Memory tube)

When the writing electron beam hits the screen with sufficient energy, many secondary electrons are emitted, ($\delta > 1$) leaving the affected areas with a positive charge. The flood guns emit electrons with low energy. The collimator bands (annular electrodes) ensure, that these slow electrons are evenly distributed over the target. When these electrons hit the phosphor, it will get charged negative, until the point that the electrons are caught by the collector and a stable situation is reached. If the flood gun electrons hit the positively charged regions, they dislodge enough secondary electrons to keep these areas positive. The released secondary electrons from the written area are accelerated by the positive potential of the conducting coating of the screen such, that the phosphor lightens up. If the energy of these electrons might become too high, they lose their capability of freeing secondary electrons (viz figure 1), in other words δ will remain at value 1, a stable situation. The action of the writing beam and the flood gun beams can be summarized as follows:

- The writing beam lights up the screen and dislodges many secondary electrons as it writes the waveform; the written area loses electrons and charges positive while the surrounding area remains *negative.*
- The flood gun electrons hit the unwritten areas too slowly to light the phosphor and the target charges negative. The positively charged written area attracts electrons at a higher speed dislodging enough secondary electrons to keep the phosphor lit and hold the area *positive*.

In conclusion: a location on the phosphor screen can be at either flood gun potential or at collector potential. Therefore, these tubes are referred to as *bi-stable* tubes.

The memory is erased by shortly applying a positive voltage to the screen (via the conductive layer). The screen is then fully ‘written’ by the flood-guns. Then, the screen is made negative to about the flood gun cathode potential whereafter it is slowly returned to the “ready-to-write” level.

The implementation of the afore described technique in a real CRT initially led to disappointing results. This was mainly due to charge leakage between the written area and its surroundings leading to a blurred and even a disappearing trace. A solution was found in separating the storage function and the fluorescence (“fast electron -> light”) function. This is accomplished in the *mesh memory tube*.

Mesh memory tubes

Both the writing gun and the flood guns are still present. However, apart from the course collector mesh, there is a very fine storage mesh, positioned in between the collector mesh and the phosphor screen (figure 6). The collector mesh (a) accelerates electrons towards the storage mesh and (b) collects secondary electrons emitted by the storage mesh. A highly insulating dielectric layer is deposited on the storage mesh. It is in this layer where the actual storage takes place.

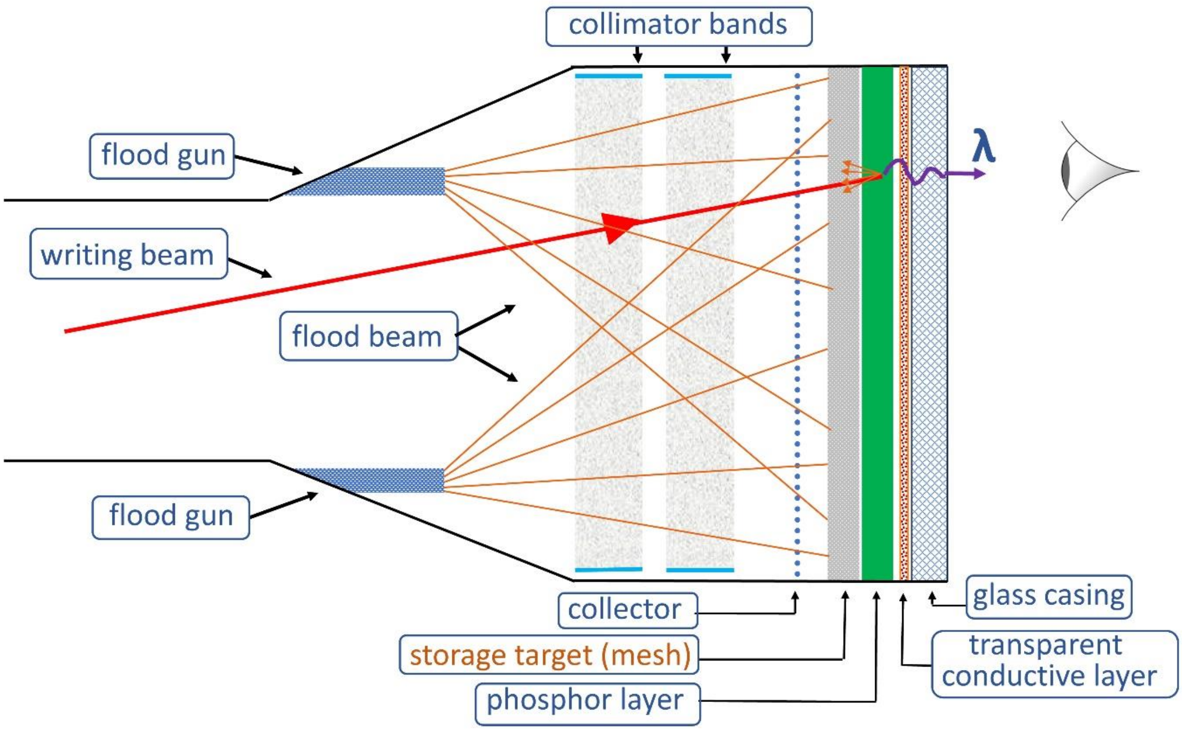

Figure 6: Lay out of the mesh memory CRT (note the added memory mesh, if compared to fig. 3)

The writing mode is similar to that of the phosphor memory tube: high energy electrons from the writing gun create local areas with a positive charge due to secondary emission from the dielectric. whereas the other regions remain negative. In the reading mode there is an accelerating potential of a few 1000 Volts between the storage mesh and the conductive layer (aluminized coating) between the phosphor screen and the glass casing of the CRT. Hence, flood gun electrons are attracted through the positively charged areas of the storage dielectric. After having been accelerated by the aluminized coating, they hit the phosphor screen thus creating a bright spot, the location corresponding to the positively charged areas of the storage target. Electrons, that do not interact with the target are returned to the collector mesh. The stored image (charge pattern) can be erased by applying a positive pulse of about 10 V to the storage mesh. By capacitive coupling the dielectric goes positive as well but will discharge soon to about zero Volts due to the flood gun electrons hitting it. After the erase pulse is finished the storage mesh drops back to the quiescent level near zero Volts. Again, by capacitive action the dielectric drops negative to about - 10 V leaving it ready for the next writing action. It should be mentioned, that, thanks to the properties of the dielectric, there is no leakage over the surface and hence the image is retained. Here the advantage of this configuration over the phosphor memory tube becomes clear.

In summary:

- The writing beam dislodges secondary electrons from the storage target; the written area charges positive while the surrounding area of the target remains negative; flood gun electrons pan through the written area of the storage target and strike the phosphor.
- During reading flood gun electrons, that pass through the areas of storage, are accelerated, and hit the phosphor screen; the remainder of the storage target blocks flood gun electrons.

The separation of the storage and fluorescence function paved the way for the realization of another useful function, viz *variable persistence*. It was mentioned that the stored charge image can be erased by applying a positive pulse to the storage mesh. By applying a series of short pulses, the image will be partly erased. By varying the width and repetition rate of these pulses we obtain an adjustable 'fading out' of the image or, in other words: a variable persistence. It then appears as if a phosphor with a very long afterglow is used. This is a very useful feature if very slow phenomena are to be observed.

Though the mesh storage principle seems to be superior to the phosphor memory principle, as will be discussed, the development of an improved phosphor screen led to the initial supremacy of this principle as will be mentioned below.

The principles of storage CRT's have been discussed in an introductory way. Further details can be found in [3].

Early development of storage CRT's

In two advertisements of 1956 the Memotron CRT was introduced ([4], [5]). It was a device produced by Hughes Aircraft and developed by Andrew Hall, who, after pioneering work at the US Naval Research, had joined Hughes in 1950. The Memotron is a memory mesh type storage CRT as discussed above. It was used in the Memoscope 104, produced by Hughes aircraft. The instrument is described in more detail in [6]. In our collection, we have an example of both the Memotron type 6498 (figure 7) and the Memoscope 104 (figure 8). The writing speed was 4 µs/cm. Further details on this tube can be found in [7].

Figure 7: The Hughes Memotron type 6498 as present in our collection.

The Memotron appeared to be difficult to produce so the yield was rather low. Furthermore, it a was rather fragile device and critical to be used.

Figure 8: The Hughes 104 Memoscope (1956) as present in our collection.

Figure 9: The English Electric "REM-scope" (1963) as present in our collection.

Another early storage CRT was the type E702A produced by English Electric Valve Company, Chelmsford, UK ([8],[9]). It was a -mesh memory type tube. It was used in the so-called REM-scope, produced by Cawkell Research and Electronics Ltd., London, UK. In our collection we have a copy of this apparatus figure 9). The writing speed was 0.4 µs/cm.

In the meantime, a researcher from Hughes Aircraft, Bob Anderson, joined the famous oscilloscope manufacturer Tektronix, where he returned to the principle of the phosphor memory tube. He discovered, that by depositing the phosphor layer in a well-defined scattered way (mutually isolated phosphor dots), a stable charge pattern could be realized, hence avoiding the cumbersome production of a multi electrode tube as the mesh storage CRT ([2]). This led to the highly successful Tektronix 564 storage oscilloscope, introduced in 1962 [10] and later followed by the Tektronix 549 in 1965 [11]. An example of this oscilloscope can be found in our collection as well (figure 10).

The new phosphor memory type CRTs were very solid and much easier to produce. Furthermore, they were easier to use. The development of these tubes led to a new series of oscilloscopes as well as graphic terminals for computers, such as the Tektronix 611 (1967), 601 (1969), 4010 (1972) and 4014 (1974). These tubes appeared to be very successful. However, their writing speed (maximally in the order of 2 µs/cm) did not meet the increasing need for the storage of faster signals.

Figure 10: The Tektronix 549 storage oscilloscope; note the split screen allowing for one half of the screen as storage and the other half for conventional display as present in our collection.

To achieve higher writing speeds developers returned to the mesh memory type CRT's. This allowed also for the introduction of oscilloscopes with variable persistence as mentioned previously. Hence, these tubes are often referred to as *variable persistence CRT' s*. This is somewhat confusing since it refers to a property rather than to the underlying physical principle. Tektronix applied these CRT' s e.g., in their 7613 oscilloscopes [12] and the 607 X-Y storage display unit [13]. The memory mesh technique with its inherent variable persistence feature was also employed in a.o. the Philips PM3243 (1977) as present in our collection [14]. Although not in our collection the Hewlett Packard HP 141B mainframe (1966) and the HP 180A (1967) should be mentioned as well as being examples of the early HP variable persistence storage oscilloscopes ([15], [16]. [17])

Later developments and conclusion

The wish for ever increasing writing speeds finally led to the development of the so-called *transfer storage* CRT. In this CRT the functions of "writing on a target" and "reading from a target" are separated. This technique was developed by Tektronix around 1972 and implemented in the Tektronix 7623 [18]. The maximum writing speed was 10 ns/div. Even faster writing speeds were achieved by the highly advanced scan-converter tubes as been used in e.g., the Tektronix 7250 [19], which was previously described in [20]. These instruments mark the end of the analogue storage era. The next generation of instruments is characterized by digital storage of measurement data using high-speed A/D-converters and solid-state memories. This leads to the conclusion, that all modern digital oscilloscopes are in fact storage oscilloscopes.

Acknowledgment

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