

# Partial Translation<sup>1</sup> of V.F. Kovalenko's "Physics of Heat Transfer and Electro- Vacuum Devices", Ch. 7 ("Pulsed Heating")

Boris Podobedov

## 1.0 Surface Destruction due to Pulsed Heating

### 1.0.1 Problems increasing pulsed power

Attempts to increase pulse power, duration or energy lead to the electrode destruction in EVD (electro-vacuum devices). This limits further growth of pulsed power for klystrons, magnetrons, pulsed light sources and other types of EVD. This barrier has a significant practical value. For example, it was possible to increase the output power for CW klystrons from 1kW [1] to 1MW [2] over the last two decades. However, during the same period of time the maximum output power of pulsed klystrons has only increased from 20MW [3] to 38MW [4]. The reason limiting further growth of output power is the destruction of metal by pulsed heating.

The metal surface of an EVD heats up during each pulse and cools down in between the pulses. Expansion and contraction of the surface causes internal stresses which in turn create non-uniformities. Their amount rises with the number of pulses. When the latter is high enough, the non-uniformities join together and create microcracks. Microcracks make heat conduction more difficult causing a sharp rise in the surface temperature so that the outer layer starts to melt, spray out, and evaporate. Metal spray and evaporation from anodes and collectors leads to intensive metal condensation onto isolators and cathodes. It also causes electrical breakdown and eventually makes devices fail. This chapter is devoted to these phenomena of metal destruction induced by pulsed heating.

Let's say a few words on terminology. The pulsed heating we consider corresponds to a typical regime of EVD widely used in radar applications. Specifically, we are talking about pulse durations on the order of 1  $\mu$ s with a time between the pulses of about 1 ms.

### 1.0.2 Pulsed heating specifics

During pulsed heating contrary to a steady state process only a thin outer layer gets heated. Its temperature doesn't have time to reach a stationary value. Another difference of pulsed heating regime (from cyclic heating and also from typical mechanical applications)

---

1. Some of the material in Ch. 7 namely paragraph 7.2 considers the specifics of electron flux heating and thus doesn't appear to be of much interest to ARDB. Results of 7.3 seem to agree with what has been calculated by our group. This is why these two paragraphs are not translated to any level of detail (B.P.)

is that a very large amount of pulses (up to  $10^{11}$ ) is required for normal operation of an EVD.

### 1.0.3 Three regimes of pulsed heating

One can distinguish three groups of pulsed heating regimes.

1. Small impulse power (very little metal evaporation and no permanent damage).
2. Large impulse power (small evaporation in the beginning; after a certain number of pulses breakage of the metal surface accompanied by intensive evaporation).
3. Ultra large impulse power (power per unit area up of  $1-100\text{MW}/\text{cm}^2$ ). Used for welding, cutting and drilling with electron beam.

Here, we only consider the second group.

## 2.0 Electron penetration depth

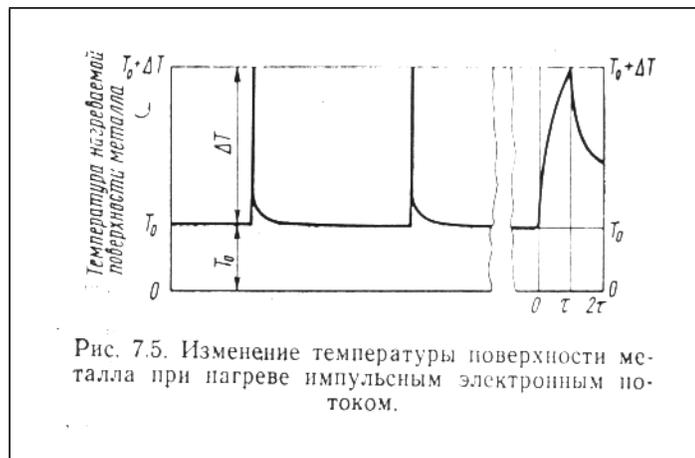
Electron penetration depth is important. From different experimental data one can derive a simple dependence

$$\rho\delta = 10^{-5}E^{1.5}, \quad (7.2)$$

where  $\rho$  - density,  $\text{g}/\text{cm}^3$ ;  $\delta$  - penetration depth, cm; E - electron energy, keV. This formula is applicable for electron energies in the range of 0.5MeV to 3GeV.

## 3.0 Pulsed heating due to electron flux

Consider metal heating with an electron flux. The metal surface temperature is changing in time as shown on fig. 7.5.



**FIGURE 7.5: Surface temperature vs. time during pulsed heating**

In this paragraph we concentrate on the calculation of  $\Delta T$  - the difference between the maximum and minimum surface temperatures. Solution of heat conductance equation for a semi-infinite body and a rectangular heat pulse shows that by the end of the pulse the surface temperature rises by

$$\Delta T = \frac{0.27P\sqrt{\tau}}{\sqrt{\lambda\rho c}}, \quad (7.3)$$

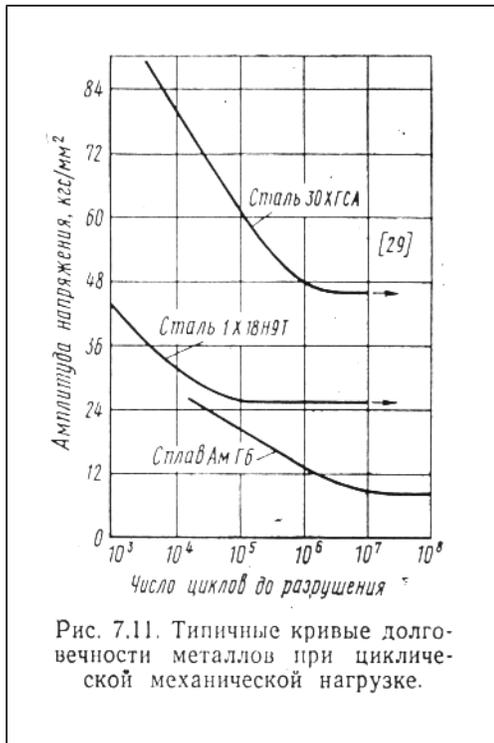
where  $\Delta T$  - pulsed temperature rise,  $^{\circ}\text{C}$ ;  $P$  - flux power,  $\text{W}/\text{cm}^2$ ;  $\tau$  - pulse duration, s;  $\lambda$  - heat conductance,  $\text{cal}/(\text{cm s})$ ;  $c$  - heat capacity,  $\text{cal}/(\text{g } ^{\circ}\text{C})$ ;  $\rho$  - density,  $\text{g}/\text{cm}^3$ .

For pulsed (contrary to CW) heating  $\Delta T$  can not be changed by variation of neither metal thickness nor cooling parameters.

## **4.0 Metal destruction by a pulsed electron flux**

### **4.1 Analogy with cyclic mechanical stress**

The phenomenon of metal destruction by a pulsed electron flux has not been studied in detail. Therefore we take several ideas from the better developed field of mechanical destruction of materials. Studies there have shown that a metal gets destroyed due to internal strain caused by a cyclic force. It is typical for all types of cyclic forces (expansion, contraction, bending etc.) that a metal doesn't break immediately but it rather does so after certain (fairly large) number of pulses. Typical experimental curves [29] of stress amplitude vs. number of cycles before destruction are shown in fig. 7.11.



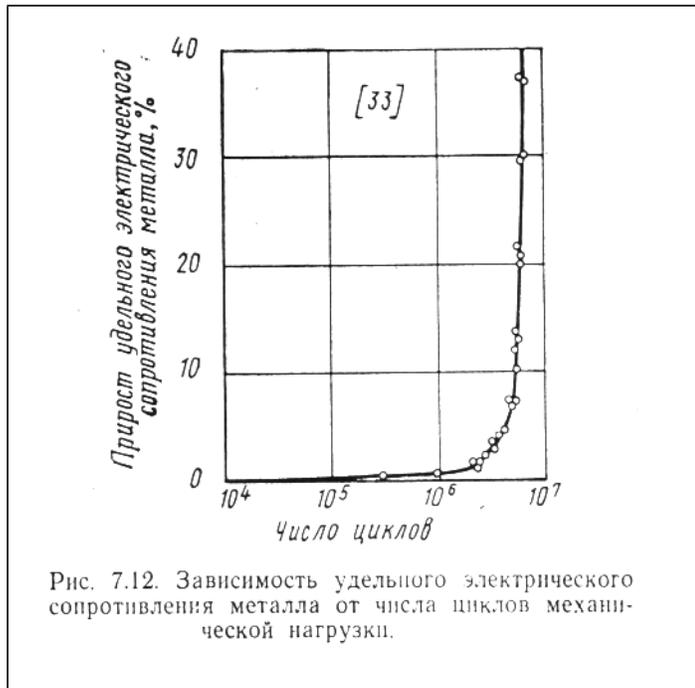
**FIGURE 7.11: Typical curves of metal lifetime under the cyclic stress (Stress amplitude (kgs<sup>2</sup>/mm<sup>2</sup>) vs. number of cycles before destruction for two kinds of steel and an alloy)**

a. kgs  $\equiv$  10kg $\times$ g  $\equiv$  9.807Newtons(B.P.)

Stress amplitude is less than a certain “safety threshold” in the horizontal region. There metal only experiences deformations which do not cause fatigue and do not lead to destruction. When the stress amplitude exceeds the safety threshold it causes plastic deformations. Those when accumulated lead to the metal destruction. Horizontal region corresponds to the so-called elasticity limit. There are several different definitions of this concept. We will define it as a stress amplitude that causes the first plastic (residual) deformation (more discussion on this will follow).

Metallic surface heated by a pulsed electron flux eventually gets destroyed. This destruction doesn’t occur immediately but rather after a certain amount of pulses, similar to the one caused by mechanical stress. The number of pulses needed for a surface to break depends on the pulsed temperature rise. This dependence has horizontal and linear slope regions, i.e. there is a “safe” pulsed heating temperature rise. If the latter does not exceed a certain safe limit then the pulsed electron flux doesn’t destroy the metal. Below we will describe physical phenomena that define both regions. We will also suggest formulas to calculate them.

Let us mention another phenomenon found in mechanical stress studies. Mechanical stress causes a large number of microscopic cracks to be created inside a metal. As the number and the size of those cracks grow many other properties of metal change. For example the change in electrical resistance [33] is shown on 7.12.



**FIGURE 7.12 Percent growth of electrical conductance vs. number of cycles of mechanical stress**

For mechanical stress studies the electrical resistance increase is considered as a side effect which can be used for diagnostics. For electron flux heating, however, this phenomenon has a principle significance. Since the cracks cause the electrical resistance increase they also decrease the heat conductance of a metal. This leads to an increase of both equilibrium and pulsed components of temperature followed by melting and intensive evaporation of the outer surface.

#### 4.1.1 Safe pulsed temperature rise

The simplest calculation of a safe pulsed temperature rise is the following. By the end of the pulse the surface is heated but the main body of the metal has no time to warm up. Consider a small surface volume of size  $l \times l$  and depth  $d$ . Let us assume that it is uniformly heated and its temperature exceeds the one of a main body by  $\Delta T$ . If nothing prevented it from expansion its length and width would grow by

$$\Delta l = \alpha l \Delta T. \quad (7.12)$$

However, since it is connected to the rest of the metal those two cannot change. This is why a contraction stress occurs in the metal

$$\Delta l = \frac{\sigma l}{E} (1 - \mu), \quad (7.13)$$

where  $\sigma$  is stress,  $E$  is a Young modulus, and  $\mu$  is Poisson's ratio. Combining 7.13 and 7.12 we get

$$\sigma = \frac{\alpha E \Delta T}{1 - \mu}. \quad (7.14)$$

For pulsed heating not to destroy a metal it is necessary that the stress amplitude not exceed its elasticity limit for pulsed contraction. So, the safe temperature boundary is defined as

$$\Delta T_s = \frac{\sigma}{\alpha E} (1 - \mu). \quad (7.15)$$

The physical meaning of  $\sigma$  is elasticity limit. However, one cannot directly use the values of  $\sigma$  from reference books in 7.15. This formula requires a dynamic limit of elasticity for compression stress at the safe temperature. Reference literature, however, usually quote static  $\sigma$  for expansion of heat-treated metal at room temperature. Those two values may differ by a significant factor because

1. dynamic  $\sigma$  is a lot higher than a static one [33]
2.  $\sigma$  for compression could be bigger than the one for stretching [34]
3.  $\sigma$  for deformed metal is several times higher than for heat-treated metal [35]
4.  $\sigma$  goes down with temperature [35]

Therefore  $\sigma$  could be several times higher than  $\sigma_{\text{ref}}$  given by reference books. Since modern references do not have values for  $\sigma$  let's assume  $\sigma = 3\sigma_{\text{ref}}$ . Substituting this and  $\mu = 1/3$  in 7.15 we get an approximate formula

$$\Delta T_s = \frac{2\sigma_{\text{ref}}}{\alpha E}, \quad (7.16)$$

where  $\Delta T_s$  is a safe amplitude of pulsed temperature rise,  $\sigma_{\text{ref}}$  - elasticity limit from reference books (static elasticity limit for stretching of heat-treated metal at 20 °C); E - Young modulus,  $\alpha$  - linear expansion coefficient at 20 °C. Similar formula was published in 1960 [36]. However, it gives factor of 2-3 lower values than the experiment [37]. This is why we hope 7.16 will have a better agreement with experimental data. Let's calculate  $\Delta T_s$  for metals widely used in pulsed EVD. There is some spread in values for  $\sigma_{\text{ref}}$  and E published in different reference books. We use the values from [38] (actively used by EVD designers) and [39]. Calculations of 7.16 are shown in table 7.5.

**TABLE 7.5: Safe pulsed heating temperature rise. Rows: Cu, Mo, W. Columns:  $\sigma_{ref}$ , kgs/cm<sup>2</sup>;  $E^a$ , kgs/cm<sup>2</sup>;  $\alpha \times 10^6$ , 1/°C;  $\Delta T_s$ , °C.**

Металл	$\sigma_T$ , кгс/см <sup>2</sup>	$E$ , кгс/см <sup>2</sup>	$\alpha \cdot 10^6$ , 1/°C	$\Delta T_6$ , °C
Медь	12	13 130	16,5	110
Молибден	55	33 630	5,5	595
Вольфрам	77	41 500	4,45	843

- a. This could be a typo in the original. Probably, the correct units are kgs/mm<sup>2</sup>.  
According to modern references  $E=9 \times 10^5$  kgs/cm<sup>2</sup> for copper. (B.P.)

The results are amazing. Copper which sustains continuous heating for up to about 500 °C in CW EVD breaks by pulsed electron flux causing a surface temperature increase of only  $\Delta T > 110$  °C. Tungsten which sustains 2500 °C heating in light bulbs breaks under pulsed heating when  $\Delta T > 843$  °C. We conclude that for any metal the safe temperature for pulsed heating is significantly smaller than the safe temperature for continuous heating. For the latter the “absolutely safe” temperature (one monolayer evaporates in 30,000 hours) is about 1/2  $T_{melting}$ . For pulsed heating it’s about 1/3  $T_{melting}$  (table 7.6)

**TABLE 7.6: Relation between the safe pulsed heating temperature and melting temperature (rows: Cu, Mo, W; columns:  $\Delta T_s$ , °C;  $T_0$ , °C;  $T_0 + \Delta T_s$ , °C;  $T_0 + \Delta T_s$ , К;  $T_{melt}$ , К;  $(T_0 + \Delta T_s) / T_{melt}$ )**

Металл	$\Delta T_6$ , °C	$T_0$ , °C	$T_0 + \Delta T_6$ , °C	$T_0 + \Delta T_6$ , К	$T_{пл}$ , К	$\frac{(T_0 + \Delta T_6), К}{T_{пл}, К}$
Медь	110	70	180	453	1356	0,33
Молибден	595	70	665	938	2895	0,34
Вольфрам	843	70	913	1186	3683	0,33

From 7.3 we can find a safe value of  $P \sqrt{\tau}$ . Pulsed heating below this value doesn’t cause surface destruction. Results are shown in table 7.7.

**TABLE 7.7: Safe value of  $P\sqrt{\tau}$  (rows: Cu, Mo, W; third column is in  $W \times s^{1/2}$ )**

Таблица 7.7			
Безопасная величина $P\sqrt{\tau}$			
Металл	$\Delta T_0, ^\circ C$	$V_{\lambda pc}$	$P\sqrt{\tau},$ Вт·с <sup>1/2</sup>
Медь	110	0,884	360
Молибден	595	0,500	1100
Вольфрам	843	0,485	1510

The values of  $\Delta T_s$  and  $P\sqrt{\tau}$  in tables 7.5 and 7.7 cannot be considered very accurate, they will be refined as more experimental data becomes available. However, there is no doubt that those values are approximately correct.

#### 4.1.2 Number of pulses before surface destruction

Experiments show that pulsed heating with  $P\sqrt{\tau}$  exceeding the safe value for a particular metal eventually leads to surface destruction. In the beginning the metal works just fine but after a certain number of pulses its surface temperature rises sharply. This is where so-called erosion begins, i.e. metal peels off, melts, intensively evaporates and sprays out from certain surface areas. Let us find a physical model which explains the effects observed and gives the number of pulses vs. heat load dependence. Such a theory was proposed by V.A. Khmara in 1970 [40,41]. The main ideas are described below.

The equilibrium concentration of empty vacancies in metal is given by

$$\frac{n_v}{n} = a \exp\left(-\frac{U_v}{RT}\right), \quad (7.17)$$

where  $n_v$  - number of vacancies per mole;  $n$  - number of atoms per mole;  $U_v$  - vacancy creation energy, cal/mole;  $R$  - 2cal/mole $\times$ <sup>0</sup>C.

When the temperature cycles  $N$  times from  $T_1$  to  $T_0$  the number of vacancies irreversibly accumulated in metal is

$$\frac{\Delta n_v}{n} = NA \left( \exp\left(-\frac{U_v}{RT_1}\right) - \exp\left(-\frac{U_v}{RT_0}\right) \right), \quad (7.18)$$

where  $A$  is a constant.

As the vacancies accumulate the bonding energy which holds the atoms together goes down. In a mole of metal this energy decreases from evaporation energy  $U$  down to

$$\Delta U = U - U_v NA \left( \exp\left(-\frac{U_v}{RT_1}\right) - \exp\left(-\frac{U_v}{RT_0}\right) \right). \quad (7.19)$$

The time before the metal breaks apart (destruction time) is given by

$$t_d = 10^{-13} \exp\left(\frac{\Delta U}{RT}\right). \quad (7.20)$$

Energy  $\Delta U$  doesn't change between the pulses. If we assume  $t_d=0.01s$  and is equal to the time between the pulses we get

$$\Delta U \approx 25RT_0, \quad (7.21)$$

and from 7.19

$$25RT_0 = U - U_v NA \left( \exp\left(-\frac{U_v}{RT_1}\right) - \exp\left(-\frac{U_v}{RT_0}\right) \right). \quad (7.22)$$

There is no data on  $U_v$  in the reference literature. Let's derive it as a function of evaporation energy  $U$ . The simplest physical model is the following. Consider a cubic crystal lattice. Each atom has six neighbors. If a vacancy completely destroys the bond between an atom and one of its neighbors but doesn't affect the other bonds then the energy of an atom drops by  $1/6$ . The same drop is experienced by the neighbor with which the bond was lost. Therefore, the vacancy creation energy is  $1/6 + 1/6$  of the full bonding energy of an atom, which is equal to evaporation energy. Comparison of evaporation energies and vacancy creation energies [41] showed that

$$U_v = \frac{U}{3}. \quad (7.23)$$

Experimental studies of  $A$  for some metals showed that  $A < 50$ . Substituting  $U_v=U/3$ ,  $A=50$ ,  $R=2$  into 7.22 we get the main formula

$$50T_0 = U - \frac{50}{3} NU \left[ \exp\left(\frac{-U}{6T_1}\right) - \exp\left(\frac{-U}{6T_0}\right) \right]. \quad (7.24)$$

V.A. Khmara [41] uses  $t_d=1s$  and  $U_v=0.3U$ , which gives a slightly different (B.P.) formula. We think, however, that our values of  $t_d=0.01s$  and  $U_v=U/3$  are more relevant.

For most cases the second term in square brackets in (7.24) is negligible. This allows for a more convenient representation of (7.24)

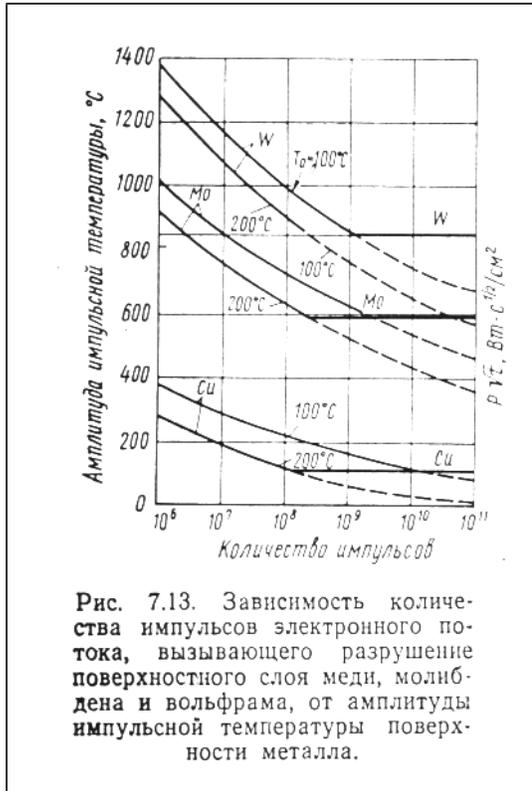
$$\Delta T = \frac{0.0723U}{\log N + \log \frac{U}{U - 50T_0} + 1.22} - T_0, \quad (7.25)$$

where  $\Delta T$  - pulsed temperature rise,  $^{\circ}\text{C}$ ;  $T_0$  - equilibrium T, K;  $U$  - evaporation energy, cal/mole;  $N$  - number of pulses required for surface destruction.

It follows from the theory above that metal destruction should occur for any value of temperature, i.e. for any electron flux power. This contradicts the safe pulse heating temperature concept described earlier as well as the operational experience of low power EVD where the destruction of metal has never been observed. To remove this contradiction we will assume (contrary to [41]) that this theory only holds for region  $\Delta T \geq \Delta T_s$ .

Physically this limitation can be explained as follows. Metal has to have a sufficient number of non-uniformities for irreversible accumulation of vacancies. If a plastic deformation occurs during a pulse then it will create enough non-uniformities for irreversible vacancy accumulation. This is not the case for elastic deformation. Mathematically  $A=0$  in the elastic deformation region but it suddenly changes to  $A=50$  in the plastic region.

Let's return to the formula (7.25). Calculated dependencies of  $\Delta T$  vs.  $N$  for Cu, Mo and W are shown in fig. 7.13. Also shown are horizontal regions of this dependence corresponding to a safe pulsed temperature rise (table 7.5).



**FIGURE 7.13: Pulsed temperature rise in °C vs. number of pulses**

Reference [41] doesn't take into account the theory limitations caused by the elasticity limit. To show the error if one neglects that boundary, we dashed the falling curves beyond the applicability region of (7.25), i.e. where  $\Delta T < \Delta T_s$ .

Similar curves are drawn on (7.14) for pulsed power vs. number of pulses. Note that from 7.3 and 7.25 for  $\Delta T \geq \Delta T_s$  the maximum value of  $P\sqrt{\tau}$  is

$$P\sqrt{\tau} = \frac{\sqrt{\lambda\rho c}}{0.27} \left( \frac{0.0723U}{\log N + \log \frac{U}{U - 50T_0} + 1.22} - T_0 \right). \quad (7.26)$$

Curves shown on 7.13 and 7.14 should be considered approximate. They must be refined according to experimental data. However, as a first order approximation they cause no doubts.

The theory considered in this chapter doesn't take into account temperature gradients and thus cannot find the destruction depth. It also finds only the number of cycles before destruction and doesn't study the kinetics of the destruction process. Therefore this theory should only be thought of as a first stage of development of a more general one. The full theory of metal destruction by pulsed electron fluxes will be developed in the near future.

## 5.0 Chapter 7 - Conclusion

Maximum temperatures of electrodes in CW EVD are limited by the metal evaporation rate (see Chapters 3, 4, 5). For a pulsed regime, maximum temperatures are much lower than in CW. They are defined by the creation rate of non-uniformities. The increase in number of non-uniformities leads to metal destruction. EVD devices break not because of metal surface destruction or single particles leaving the surface but rather because of the rapid temperature rise of surface elements separated by cracks from the main body of the metal.

Effects caused by pulsed heating often surprise both designers and consumers of vacuum electron tubes. For example, a powerful amplifying tetrode used to work reliably for thousands of hours in the output cascade of a radio transmitter. However, it started malfunctioning one hundred hours after it was installed in a TV transmitter. The immediate cause of failure was the evaporation of a copper anode.

Therefore, copper in the tetrode didn't evaporate when it worked in CW for radio transmission but it evaporated intensively during TV transmission use. As it turned out evaporation was caused by synchro-impulses that transmit after each frame of a TV picture broadcast. These pulses caused non-uniformities to accumulate in the copper surface layer during the first hundred hours of normal work and then led to rapid evaporation of that layer.

Magnetron cathodes have a smaller lifespan for pulsed devices than for those working in CW. It is possible that one of the reasons decreasing the lifetime is pulsed heating of the cathodes caused by reversed electron bombardment.

Pulsed heating may be created not only by electron flux but also by conducting currents. There have been cases of design versions of EVD that broke down because of pulsed heating of metallic films on dielectric. Those films are sometimes made to form a desired electric field pattern. In other cases they are unintentionally created during the soldering process. Anode voltage turn-on causes a film to charge. When it charges or discharges it has currents flowing inside. These currents heat up the film. It tries to expand but the ceramic underneath prohibits it. Consequently, the film gets deformed and after many deformations loses connection with the ceramic. This prevents a heat flux into the latter. The film overheats, evaporates and causes electric breakdown. Similar phenomena are observed in computer chips namely thin film wires coated on a dielectric burn out after many current pulses have flowed through.

All these examples show the wealth of pulsed heating effects in modern engineering applications. To find the laws that govern those effects and to find the theory and calculation methods for those phenomena is a task for the immediate future.

## 6.0 Chapter 7 - References

10. Glocker R. Die Abhängigkeit der Reichweite der Elektronen von ihrer Energie. — *Z. Naturforsch.*, 1948, S. p. 147—151.
  11. Evans H. D. An absorption comparison of the  $\beta$ -particle spectra. — *Proc. Phys. Soc.*, London, 1950, v. 63, p. 575—585.
  12. Gleason G. I., Taylor J. D., Tabern D. L. Absolute beta counting at defined geometries. — *Nucleonics*, 1951, v. 8, p. 12—21.
  13. Young J. E. Penetration of electrons in aluminum oxide films. — *Phys. Rev.*, 1955, v. 103, № 2, p. 291—293.
  14. Броштен И. М., Фрайман Б. С. О пробоге кинеровольтовых электронов в твердых телах. — «ФТТ», 1961, т. 3, № 4, с. 1122—1124.
  15. Morbitzer L., Scharmann A. Messung der Eindringtiefe von Elektronen und Ionen in dünnen Aufdampfschichten. — *Z. Physik*, 1964, Bd. 181, N 1, S. 67—80.
  16. Katz L., Penfold A. S. Range-energy relations for electrons and the determination of beta-and-point energies by absorption. — *Revs. Modern Phys.*, 1952, v. 24, № 1, p. 28—44.
  17. Flammerfeld A. A relation between energy and range for  $\beta$ -rays of small and medium energy. — *Naturwiss.*, 1946, v. 33, p. 280—281.
  18. Weber K. H. Eine einfache Reichweite-Energie-Beziehung für Elektronen im Energiebereich von 3 keV bis 3 MeV. — *Nuclear Inst. a. Methods*, 1964, v. 25, № 2, p. 261—264.
  19. Holliday J. E., Sternglass E. J. New method for range measurements of low-energy electrons in solids. — *J. Appl. Phys.*, 1959, v. 3, № 9, p. 1428—1431.
  20. Kanter H., Sternglass E. J. Interpretation of range measurements for kilovolt electrons in solids. — *Phys. Rev.*, 1962, v. 126, № 1, p. 620—626.
  21. Попов В. К. Особенности взаимодействия потока электронов больших энергий с веществом. (Обзор). — «Электронная техника. Сер. 1», 1967, вып. 11, с. 109—126.
  22. Стародубцев С. В., Романов А. М. Прохождение заряженных частиц через вещество. Ташкент. Изд-во АН УССР, 1962.
  23. Броштен И. М., Фрайман Б. С. Впорочная электронная эмиссия. М., «Наука», 1965.
  24. Карслоу Г., Егер Д. Теплопроводность твердых тел. Пер. с англ. М., «Наука», 1964.
  25. Тактин С. А. Некоторые вопросы теплотехники электровакуумных приборов. Канд. дисс. Киев, ИРЭ УССР, 1960.
  26. Thermophysical properties of high temperature solid materials. The MacMillan Company, N. Y., Collier-MacMillan Limited, London, 1967, v. 1.
  27. Захаров М. И. Нагрев тела импульсным электронным потоком. — «Электронная техника. Сер. 1», 1971, вып. 11, с. 12—22.
  28. Денискин Ю. Д. Влияние проникновения электронов в твердое тело на импульсный нагрев бомбардируемой им поверхности. — «ЖТФ», 1966, т. 36, вып. 3, с. 208—510.
  29. Почтенный Е. К. К теории устойчивости металлов. — В кн.: Прочность металлов при циклических нагрузках. М., «Наука», 1967, с. 14—20.
  30. Физический энциклопедический словарь. Т. 4, с. 188, М., «Советская энциклопедия», 1965.
  31. Белиев Н. М. Сопротивление материалов. М., Физматгиз, 1959.
32. Металлы. Методы испытания на растяжение. ГОСТ 1497—61, М., 1961, с. 188.
  33. Лозинский М. Г. Применение методов низкотемпературной микроталлографии для исследования закономерностей изменения строения металлов и сплавов в процессе испытаний их на устойчивость. — В кн.: Прочность металлов при циклических нагрузках. М., «Наука», 1967, с. 44—54.
  34. Малнини Н. Н. Прикладная теория пластичности и ползучести. М., «Машиностроение», 1968.
  35. Физико-химические свойства элементов. Справочник, Под ред. Г. В. Саволова, Киев, «Наукова думка», 1965.
  36. Parkes E. W. The stresses in an elastoplastic bar subjected to a sudden change of surface temperature. — *J. Appl. Mech.*, 1961, v. 28, № 3, p. 434—438.
  37. Хмара В. А. Об оценке работоспособности металлов в условиях длительного воздействия импульсного электронного потока. — «Электронная техника. Сер. 1», 1969, вып. 12, с. 100—103.
  38. Эле В. Технология электровакуумных материалов. Пер. с нем. М.—Л., «Энергия», 1962.
  39. Koster W. Die Temperaturabhängigkeit des Elastizitätsmoduls reiner Metalle. — *Z. Metallkunde*, 1948, Bd. 39, N 1, S. 1—9.
  40. Хмара В. А. Теория разрушения металла при импульсной электронной бомбардировке. — «Электронная техника. Сер. 1», 1970, v. 12, с. 71—77.
  41. Хмара В. А. К вопросу о долговечности материала анода мощных импульсных электронных приборов. — «Электронная техника. Сер. 1», 1971, вып. 1, с. 77—82.

### СПИСОК ЛИТЕРАТУРЫ

1. Zitelli L. T., Maltzer I. A 100 kw. cw high efficiency klystron amplifier. — In: «Tubes pour hautes fréquences. Travaux du 5<sup>e</sup> Congrès international». Paris, 14—18 Septembre, 1964. Dunod Editeur, Paris, 1965.
2. Microwave product news. — «Microwave Jounl», 1970, № 2, p. 105.
3. Design and performance of a high-power pulsed klystron. — «Proc. IRE», 1953, v. 41, № 11, p. 1564—1601. Aut.: M. Chodorow, E. L. Ginzton, I. R. Nelsen, S. Sankins.
4. Stringall R. L., Lebacqz J. V. High power klystron development at the stanford linear accelerator center. — In: MOGA 70—Eight International Conference. Summaris. Amsterdam, 1970.
5. Бакис Р. Введение в технологию электроннолучевых процессов. Пер. с англ. М., «Металлургия», 1965.
6. Бакис Р. Электронно-ионнолучевая технология. Пер. с англ. М., «Металлургия», 1968.
7. Schonland V. F. The passage of cathode rays through matter. — «Proc. Roy. Soc.», 1925, v. 108, № 5, p. 745—748.
8. Glendenin L. E., Goryell C. D. — «MDDC», 1946, v. 19.
9. Libby W. E. Measurement of radioactive tracers. — «Anal. Chemistry», 1947, v. 19, № 1, p. 2—6.