TECHNICAL PAPER

Reverse Voltage Behavior of Solid Tantalum Capacitors

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Abstract:
This paper is intended to give the design engineer an understanding of the effects of reverse voltage operation on the chemical structure and life reliability of a tantalum capacitor. It also aims to show a circuit design engineer about predicting the life performance of a circuit where a tantalum capacitor is subjected to negative voltages.

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1.0 Introduction

Solid tantalum capacitors are polar devices, with an anode terminal and a cathode terminal. The voltage across these terminals should only be applied positive to anode, and negative to cathode, otherwise the capacitor will be damaged, leading to failure.

All tantalum capacitor manufacturers recommend that a continuous reverse voltage should never be placed across the capacitor terminals [1, 2, 3]. In almost all circuits, negative transients can occur during operation. There is also the possibility that the capacitor may be incorrectly inserted into a circuit or connected into a piece of equipment in such a way that a reverse voltage condition may exist. It is therefore important that the design engineer understands the possible consequences and failure mechanism, and methods of minimizing the risk of failure.

2.0 Maximum Allowable Reverse Voltage Guidelines

The allowable level of DC reverse voltage specified by tantalum capacitor manufacturers varies quite considerably. For example, one manufacturer does not give any guideline but simply advises that tantalum capacitors are never used in a circuit where a reverse voltage may be applied across its terminals [1], but another says that up to 10% of rated voltage is permissible [4].

The most common guidelines for reverse voltage are:

10% of rated voltage to a maximum of 1 volt at 25°C
3% of rated voltage to a maximum of 0.5 volts at 85°C
1% of rated voltage to a maximum of 0.1 volts at 125°C

These guidelines apply for **short excursions** and should never be used to determine the maximum reverse voltage under which a capacitor can be used permanently.

3.0 Description of Failure Mechanism

The dielectric material in a tantalum capacitor is a layer of amorphous tantalum pentoxide which is grown over the surface of the tantalum powder (anode) using electrolysis [8]. The thickness of this layer is about 60 Ångströms (6 nm) per capacitor rated volt. Then a cathode layer of semi-conducting manganese dioxide is laid down over the dielectric surface.

During normal forward voltage operation of parts, it is possible for exposed areas of tantalum metal to be re-oxidized or "repaired" to amorphous dielectric, by taking the required oxygen from the adjacent manganese dioxide cathode material. This reduces the leakage current at the fault site. Under reverse bias, this mechanism will not operate because the negatively charged oxygen species move in the opposite direction to that required for the repair mechanism.

As well as this mechanism, the removal of oxygen from the semi-conducting manganese dioxide (MnO_2) converts it locally to much higher resistance "lower oxides" such as Mn_2O_3 , Mn_3O_4 or MnO. This further isolates the fault from contributing to the total device leakage current. These mechanisms are known as "self-repair" or "healing" and contribute to the very high reliability of tantalum capacitors during normal operation.

As the device operating temperature increases, the rated voltage needs to reduce to avoid excess voltage stress across the dielectric.

Under reverse voltages, experimental evidence within AVX indicates that a component of the reverse leakage current flows in very small areas of microcracks or other defects in the dielectric layer. Although the current may only be a few microamps, it represents a very high localized current density which can cause a tiny hot-spot. This can cause some conversion of amorphous tantalum pentoxide to the more conductive crystalline form. When a high current is available, this effect can avalanche and the device may become a total short.

This heat may, as in the forward direction, be enough also to decompose a tiny local area of manganese dioxide to a high resistance "lower oxides" so a degree of "self-healing" may be noticed even in reverse. This depends on the size of the defect and the current available.

Theoretically, these mechanisms would also cause a reduction in capacitance value, but in practice, the area involved is extremely small compared with the total dielectric area, so that no change can be measured.

4.0 Commonly Asked Questions

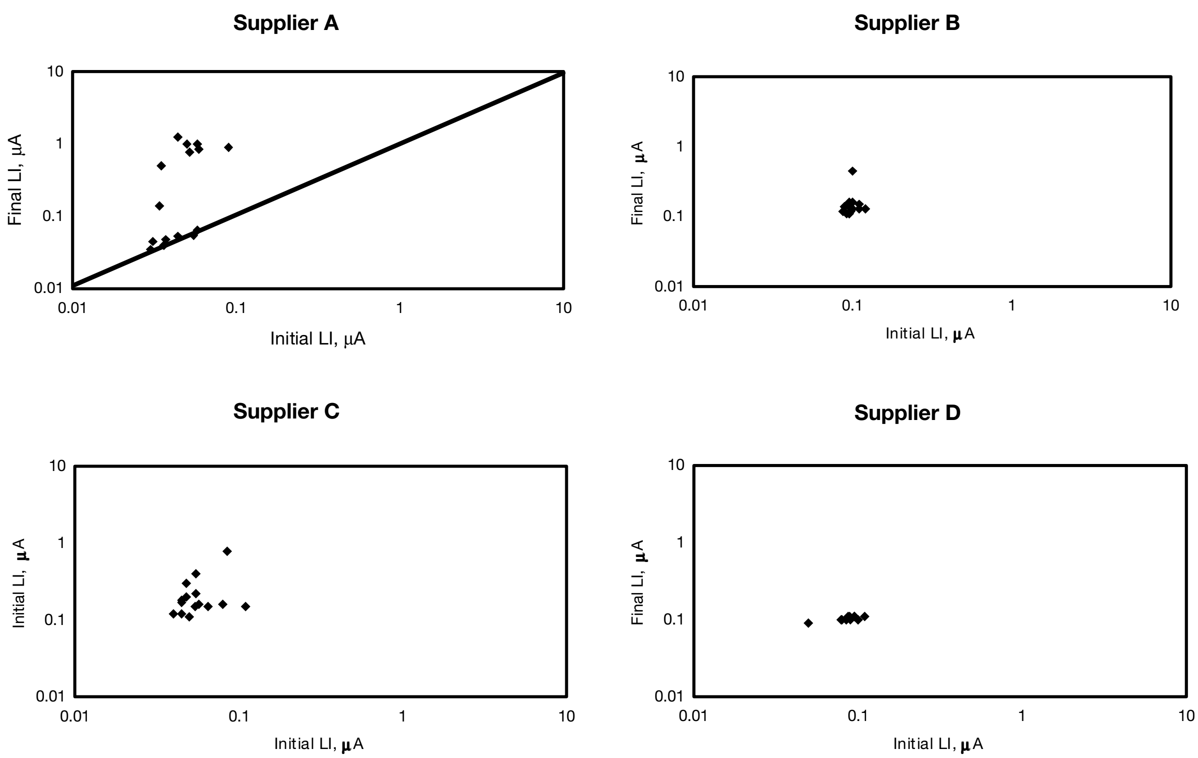
4.1 Can reverse voltage behavior be predicted by electrical measurement?

AVX has carried out extensive testing of samples taken from numerous batches under highly accelerated conditions. The results have demonstrated that, while there is some batch to batch variability, parts which failed during testing under reverse bias could not have been predicted beforehand by examination of their forward and reverse leakage current, capacitance, DF, ESR, or Impedance. See also 4.2.

4.2 Is reverse behavior generic to all manufacturers capacitors?

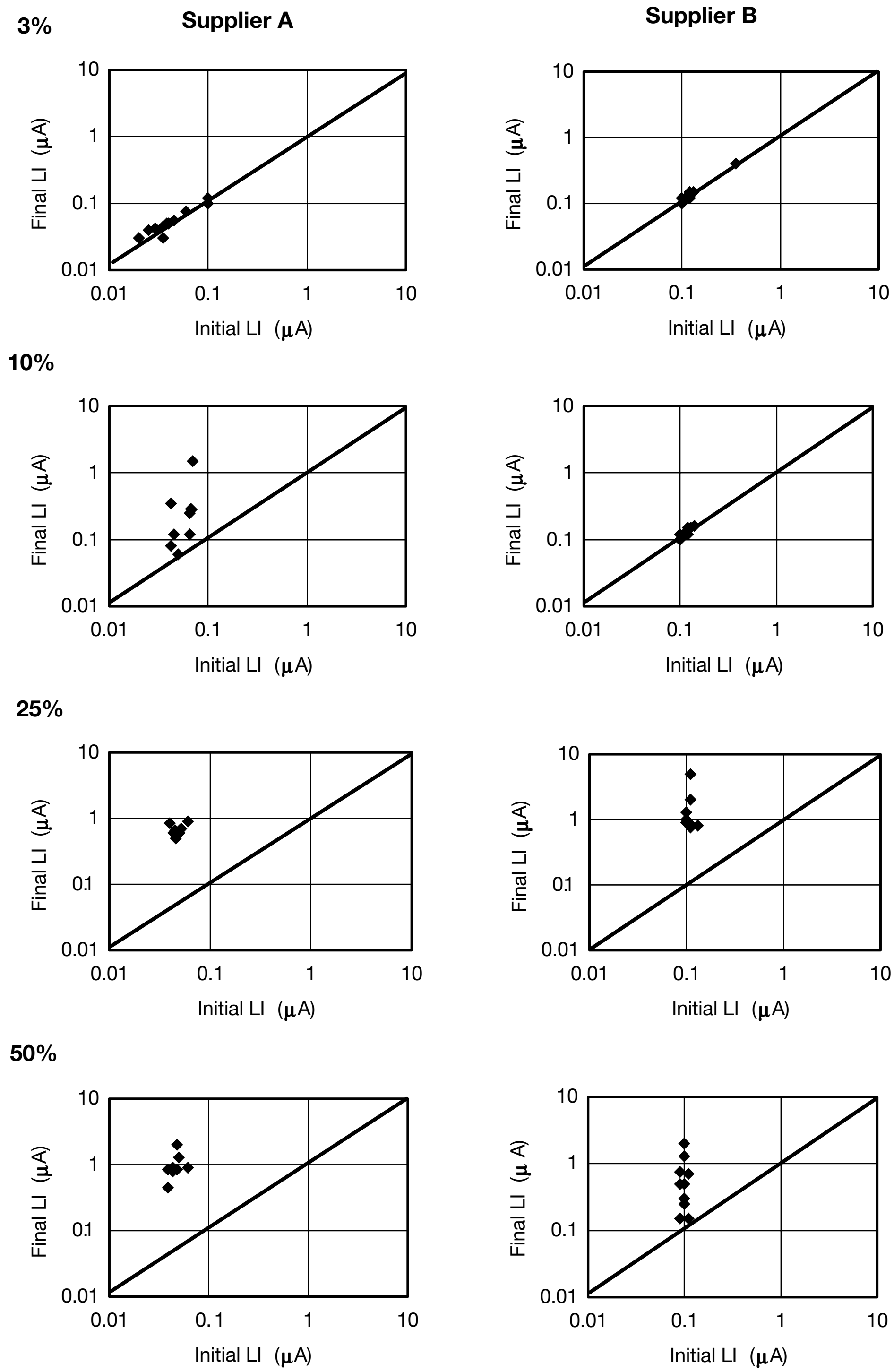
Some of the results of tests carried out for AVX are shown in Figure 1. This diagram shows the results from several manufacturers' 10 volt parts subjected to a 1 volt reverse bias (10% of rated voltage) for 48 hours at 85°C. The 45° sloping line on each chart is used to show a "no change" reference.

Figure 1



The results show that while there are some differences between manufacturers' initial leakage distributions, all experienced some increase in leakage current. They also show that for all manufacturers, parts with a low initial leakage current were as likely to increase their leakage current as units which had a higher initial leakage current. This observation is however, similar for parts tested in the forward direction.

Figure 2



		INITIAL			FINAL				
		Max	Mean	Min	Max	Mean	Min	Fail	Fuse fail
3%	A	0.097	0.046	0.018	0.123	0.06	0.027	0	0
	B	0.341	0.15	0.1	0.388	0.163	0.115	0	0
10%	A	0.071	0.054	0.033	2.053	0.483	0.073	0	0
	B	0.155	0.118	0.098	0.202	0.164	0.144	0	0
25%	A	0.072	0.046	0.033	0.823	0.565	0.365	0	0
	B	0.151	0.122	0.095	4.926	1.236	0.439	1	0
50%	A	0.072	0.043	0.03	41.04	5.292	0.467	2	0
	B	0.124	0.108	0.096	1.548	0.507	0.15	0	0
100%	A	0.103	0.057	0.018	n/a	n/a	n/a	n/a	10
	B	0.18	0.128	0.104	n/a	n/a	n/a	n/a	10

4.3 What effect does applied voltage have on the failure rate?

Figure 2 shows the results of experiments carried out on two manufacturers' products where the test voltage was varied from 3% to 100% of rated volts. The other test conditions were as in section 4.2. As can be seen the higher the reverse voltage applied the greater the average increase in the leakage current of the capacitor.

Similar results have been found by other manufacturers and users studying this subject. For example, work carried out by one Japanese tantalum manufacturer [5] showed an estimated 12-fold acceleration factor of failure rate for an increase in reverse voltage from 5% to 10%.

The table in Figure 2 indicates that at rated voltage in reverse, all the parts from two manufacturers failed, blowing the series protecting fuse.

4.4 Can the failure rate of a capacitor under reverse bias conditions be predicted?

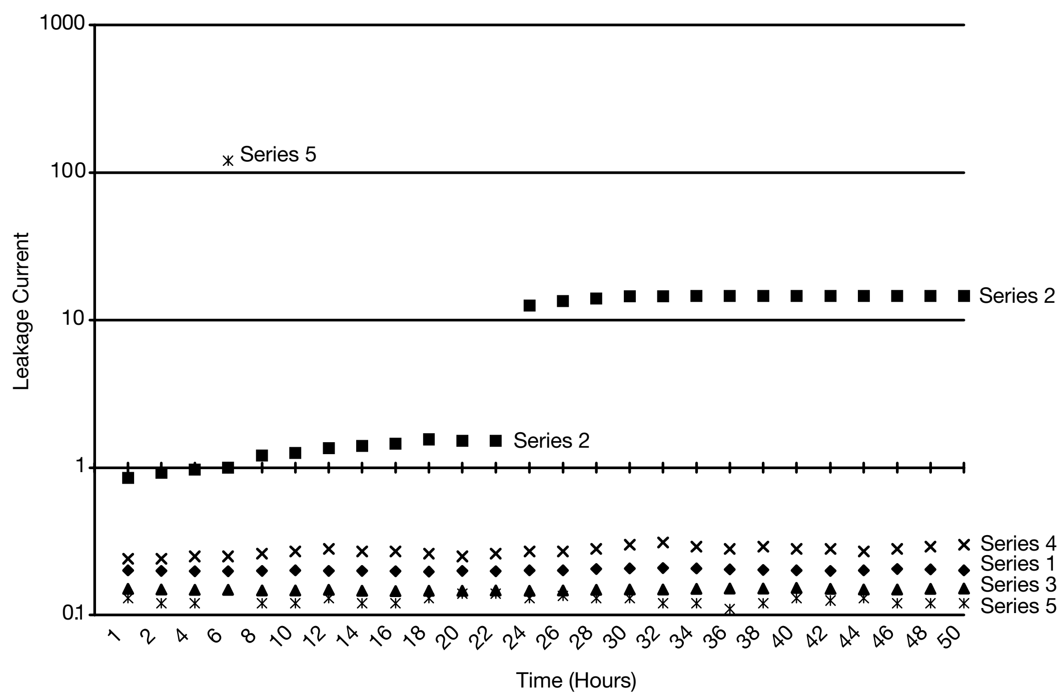
Figure 3 shows the current passing through several 10 volt tantalum capacitors subjected to a reverse bias of 1 volt at 85°C for 48 hours with an external resistance of 2.7kΩ. As can be seen, the behavior of the units varies quite considerably, with some units exhibiting a slow increase in the level of current passing, but others exhibiting sudden changes in current. Note especially the behavior of unit 5 which experienced an apparent short circuit at 10 hours but then recovered to a more normal level.

It will be seen that the failure rate for a group of capacitors subjected to reverse bias is difficult to predict, but will always be unacceptable. This makes it extremely important to prevent the possibility of any prolonged reverse voltage condition occurring, through the use of appropriate design and manufacturing controls. Methods to help achieve this are discussed in section 5.0 of this paper.

4.5 Can a part which has been subjected to reverse voltage simply be refitted in the correct orientation?

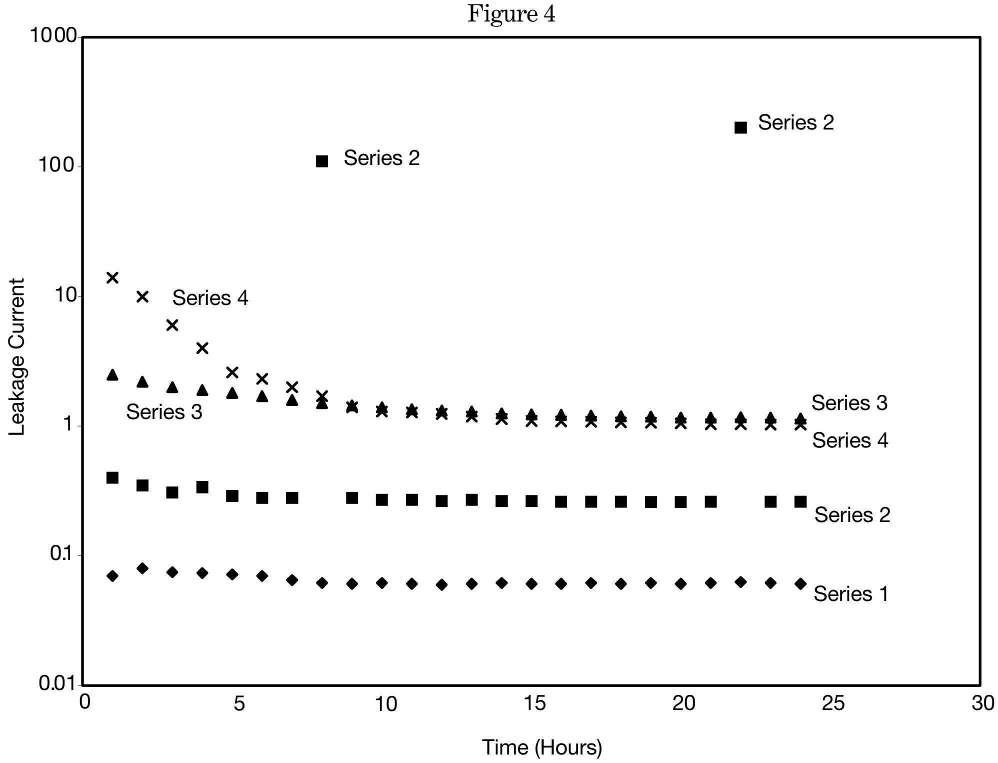
Results have shown that this is extremely inadvisable. Application of the correct polarity to a unit which has been subjected to reverse voltage can sometimes appear to heal the capacitor, but this does not always occur as shown in section 4.4. The safest option is therefore to replace any capacitor which was connected in reverse polarity. While the majority of units recover to normal levels (see Figure 3), some units continue to exhibit abnormal behavior. Figure 4 shows the results of applying forward voltage to the units from the experiment in Figure 3 at 85°C and rated volts for 24 hours. As can be seen, unit 5 becomes very low resistance twice. If the circuit impedance were low, such a condition could result in the capacitor becoming a short circuit.

Figure 3



Capacitor behavior once re-connected in correct polarity is difficult to predict, so the only safe option is to replace the unit with new taking care to observe standard reworking procedures [10].

Figure 4



4.6 What effects could be anticipated if a capacitor failed due to reverse bias?

The normal failure mode in a tantalum capacitor is increasing leakage current leading to eventual short circuit. The effect this has on the circuit will depend on the application use of the capacitor. For example, if the capacitor is being used in a high impedance timing circuit application an increase in leakage current may not be noticed. If, however, the capacitor is used as the bulk decoupling capacitor of a power rail, it may draw sufficient current to cause the power rail to dip, thus causing the circuit to shutdown.

The worst case is where the capacitor is used in a low impedance circuit and fails short circuit. In this case the unit could heat to very high temperatures leading to damage of the circuit board and smoke emission from the unit. For further details on the effects of over-heating in solid tantalum capacitors, please refer to Bob Franklin's paper [9].

5.0 Methods of Preventing Reverse Bias and Circuit Board Damage

5.1 Factors under the control of the design engineer

There are several techniques available to limit possible malfunctions. The simplest design technique is the incorporation of diode protection into the circuit. This includes full and half wave rectification, and flyback diodes for inductive loads. The only disadvantage of this technique is a voltage drop on the power rail which can be minimized to as low as 0.3 volts if a Schottky diode is used.

Another technique is to distribute several capacitors around the board instead of having a very large capacitance in one location, particularly if the probability of "ground bounce" is high as can occur on very high speed logic boards. This has the effect of minimizing the "ground bounce" by ensuring that a large charge store is near the load which is readily available. It has the advantage of cutting down noise on the board helping control electromagnetic interference (EMI).

To prevent a failed capacitor damaging the circuit board, the simplest method is to include a fuse in the power rail of the board. This technique has no drawbacks and should be employed when appropriate.

Another simple option is to use a higher voltage rated capacitor than is normally necessary. Figure 5 shows typical leakage currents for various rated capacitors under reverse voltage, and indicates that the higher the rated voltage of the capacitor, the lower the current during reverse orientation.

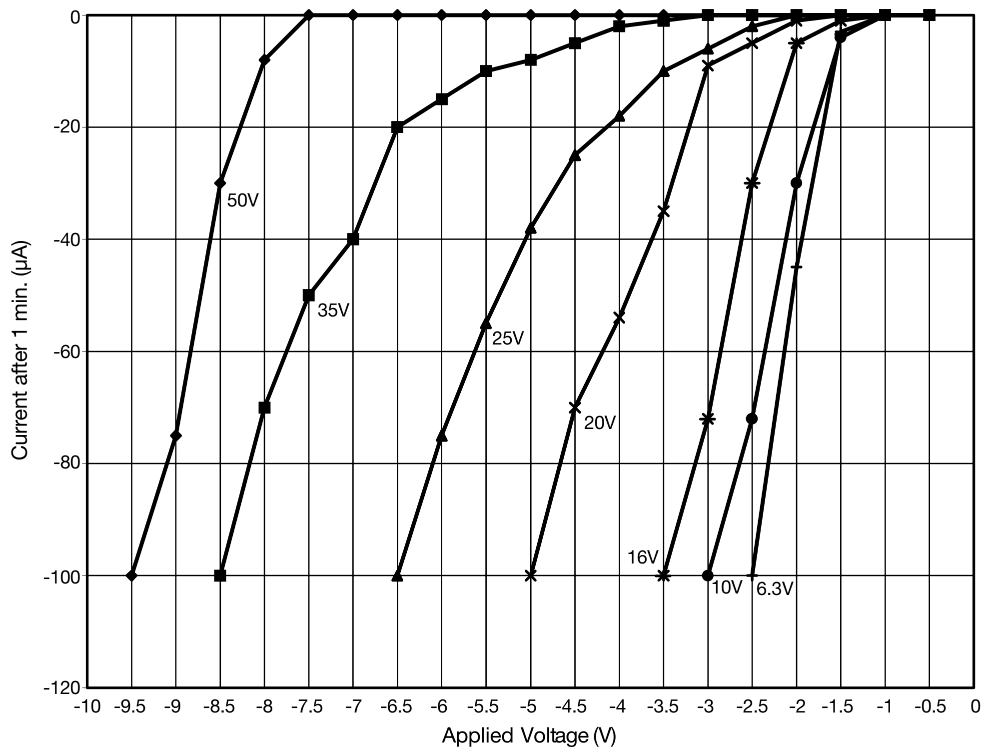
A further option is to include a resistor in the power line in order to limit the available fault current to less than 2 Watts [9]. This may not be available as a design option because of desires for circuit efficiency, but should be considered where possible.

For circuit positions when reverse voltage excursions are unavoidable, two similar capacitors in series connected "back to back" (join the two cathodes and connect the anodes to the circuit) will create a non-polar capacitor function, with, of course half the capacitance of the single device. This works because almost all the circuit voltage is dropped across the forward biased capacitor, so that the reverse biased device sees only a negligible voltage.

5.2 Factors to be considered by the manufacturing engineer

An automatic placement machine should be used to

Figure 5



prevent incorrect orientation during pick and place or insertion. Where one is unavailable, an inspection stage should be incorporated in the production process to minimize the risk of a reverse orientated part being shipped. This visual inspection should be performed by a second operator or preferably an image recognition system, to keep human error to a minimum. A printed polarity indicator on the board is often used. Such systems have been adopted by suppliers of tantalum capacitors to ensure correct orientation at the moment of insertion of parts into the packing tape or bandolier.

Test machines are now becoming available which are able to detect an incorrectly orientated part on a circuit board even when many capacitors are in parallel. These should be investigated to determine if they are suitable for use in the production process.

5.3 How the capacitor manufacturer can help

The possibility of a capacitor being supplied to the customer incorrectly orientated in the tape should be eliminated by the use of production design features and modern quality control functions and systems.

Outgoing quality levels for AVX surface mount product show that there have been no known parts incorrectly placed in the tape for many years. The situation is similar for leaded components supplied on tape. The possibility of receiving an incorrectly orientated part from the supplier's packaging is thus extremely small.

To assist supplier and user, a video readable polarity bar and laser readable voltage bar code are often built into the capacitor coding.

6.0 Conclusions

a) The reverse voltage behavior of tantalum capacitors is similar across all manufacturers, with wide batch to batch variability.

b) All precautions should be taken by the board designer and manufacturer to avoid reverse placement of a capacitor, as board damage could occur if the capacitor fails.

c) It is not possible to predict the failure rate of tantalum capacitors subjected to reverse polarity, except to say that it will probably be high.

d) A part which has been subjected to accidental reverse bias should be replaced with a new capacitor.

References

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