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4.2 EVALUATION OF A PARASITIC CHARGE-SPREADING TRANSISTOR AS A MOISTURE SENSOR.

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ABSTRACT

This paper reports on a practical evaluation of a parasitic charge-spreading transistor (CST) as a moisture sensor. The device in question has a lateral PNP structure and operates as an MOS p-channel transistor where the gate charge is built up by charge-spreading over the oxide.

A model is proposed for the dependence of relative humidity (RH) on surface conductivity, which allows extrapolation to low values of RH. This model is evaluated by experiments using the CST device.

An estimate of the time it takes for water to permeate the bulk of a plastic IC package in different environments is made using the CST.

THE OBJECTIVE OF THIS WORK

This work aims at a better understanding of the parasitic phenomenon and its dependence on voltage, humidity, temperature and surface cleanliness.

The main purpose of this work was to evaluate the parasitic charge-spreading transistor as a humidity sensor in different applications. The device could possibly be used for monitoring moisture content inside hermetically sealed encapsulations. Another possible application is to use the CST for controlling hermeticity of the packages, something that so far has been tested with helium or krypton.

A third area to be investigated was the possibility of using the sensor for characterization of plastic enclosures, in the case of water penetrating the package.

THE TEST STRUCTURE AND TEST SPECIMENS

Special test chips were made that contained a lateral PNP structure (CST). They also contained a normal MOSFET for measuring the field threshold voltage (fig. 1). Some of the testchips had a 10.000 Å thick passivation layer on top of the thermal oxide. The passivation was a phosphosilicate glass (PSG), trading name Vapox, of sandwich type. The rest had only the 10.000 Å thermal oxide.

The devices were enclosed in different encapsulations; plastic, metal can and ceramic dual-in-line packages (CERDIP).

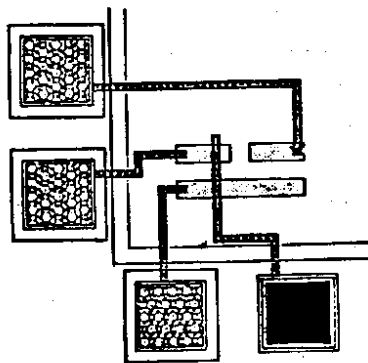


Figure 1 The CST test structure

THEORY

Charge spreading /1,2/

The voltage distribution on the oxide surface near a conductor can be described by the diffusion equation:

$$\frac{\partial^2 V}{\partial x^2} = \frac{1}{\sigma} \frac{\partial V}{\partial t} \quad \text{---(1)}$$

The solution given by:

$$V = V_0 \operatorname{erfc} \left(\frac{x^2 C}{4\sigma t} \right)^{\frac{1}{2}} \quad \text{---(2)}$$

Where: V_0 = applied bias

σ = surface conductivity

C = dielectric capacitance density

x = distance from conductor

t = time

Humidity dependence

The surface conductivity of Silicon Dioxide has been modelled and described according to the BET theory at this workshop in 1978 by R P Merrett and S P Sim. /2/ In summary the surface conductivity (s) according to the data in their report can be described by using the following expressions: (somewhat simplified)

$$m = cr / ((1-r)(1+r(c-1))) \quad \text{---(3)}$$

$$s = am * \exp(-11605 * .82 * (1 - .09m) / T) \quad \text{---(4)}$$

where

m = proportional to the amount of adsorbed water

c = $\exp(\phi/kT)$

a = constant, here 0.0001

r = relative humidity (0-1)

T = temperature (K)

ϕ = difference between the latent heat of evaporation of water and the heat of adsorption of this water, here 0.035 eV

The water adsorption on SiO₂ is plotted in figure 2 from ref /4/. This S-shaped curve looks similar to a cumulative density function curve when drawn on a linear scale. By the use of a standard log normal distribution diagram this curve could be straightened out and thus helpful when extrapolating down to low values of RH.

Equation (4) was plotted in such a diagram to see if the expression would justify the use of it for linearisation purposes. The result is shown in figure 3 and it indicates that one should expect linear relations from roughly 60%RH down to at least 2%RH provided the expression is valid.

Figure 4 shows published data on surface conductivity replotted in a log normal diagram. These experimental findings form the basis of the humidity dependence used later for evaluating the moisture sensor readings.

In the literature on the related subject, corrosion, one can find several moisture models. $\exp(a*(RH)^2)$ by Lawson or $a/(RH)^{2.67}$ by Peck have been used to linearise the data and to get moisture acceleration factors. /16,15/. Ref /5/ reported acceleration factors based upon a collection of moisture test results. In figure 5 that material has been updated with more recent data. The models are compared in figure 6.

Temperature dependence

In our computer model we have made use of the log-normal behaviour of the RH-dependence and assigned an Arrhenius function for the temperature dependence of the conductivity at 50% RH. As the activation energy varies from 0.35 to 0.8 eV depending on the RH /6/ this will result in different slopes in the log normal diagram. The lower the relative humidity the higher the activation energy. 0.35 eV is close to that of conduction in bulk water (0.34eV). Appendix A gives the fortran program that makes use of the model in order to estimate the ppm-level in a hermetic package with a CST device.

EXPERIMENTS WITH TEST CHIPS IN CerdIP PACKAGES

The time taken for the applied voltage to spread out on the oxide surface and eventually turn on the transistor was measured. (To be more precise, it was the time needed for the leakage current to reach a specified value.)

Humidity dependence

Tests were performed at room temperature with unsealed components in desiccators with different moisture contents.

12% RH: $\text{LiCl}\cdot\text{H}_2\text{O}$; 32% RH: $\text{MgCl}_2\cdot 6\text{H}_2\text{O}$; 76% RH: NaCl

When the components to be tested had been placed in the vessel, they were left for 24 hours for equilibrium to be established before any measurements were conducted.

When measurements were made at room ambient, the occasional great variations in the degree of humidity were monitored using a calibrated hygrometer.

The tests at 76% RH had to be abandoned since the turn-on time was too short for accurate measurements.

In fig 7 the turn-on time vs. relative humidity is plotted in a log-normal diagram for a few components. The results agree fairly well with the model, even though the spread between devices is relatively large.

A normal non-leaking Cerdip contains a total amount of moisture of about 1000 ppmv at 100°C according to mass spectrometric investigations. Taking into account the large surface-to-volume ratio of the ceramic package cavity, which leads to a large moisture uptake by the cavity walls, the water vapor that is free to absorb on the chip surface is around 200 ppmv /8,9,10/. This

corresponds to approximately 0.4% RH at 22°C and as the pressure inside the die cavity of a Cerdip is approximately 0.5 atm this is equivalent to 0.2% at 1 atm. For this case, log normal linear extrapolation predicts a turn-on time of 200 hours for an applied voltage of 100 V. No leakage current was detected however, even though the test chips were kept under constant bias for 500 h.

There are two possible explanations for this; either the test structure is not sensitive enough for such low conductivities, or there exists a limit below which the model is no longer valid.

Voltage dependence

The voltage dependence was examined at constant humidity and temperature (22°C, 12%). The time elapsed until the leakage current reached -150 nA was measured. The results are shown in fig 8.

The theoretical values can be calculated by keeping one point fixed (e.g. 19s, -45 V in fig 8) while adjusting the threshold voltage for best fit. As can be seen, the theoretical and experimental curves are in excellent agreement. This also seems to be a way to estimate the threshold voltage for parasitic action.

Temperature dependence

A simple test was made in order to see if the CST device would show the same temperature dependence as surface conductivity has shown /6/. A device was stored at 30% RH at varying temperatures. The turn-on time was recorded and is presented in figure 9. The device had vapour passivation. The activation energy was 0.62 eV that is very close to that reported by Koelmanns at 30% RH /Ref 6/.

EXPERIMENTS WITH "REAL" DEVICES

Instability mechanisms were reported from lifetesting of a particular circuit. It was thought to be due to parasitic action, which could be related to an unnecessary opening in the passivation layer. The chip layout is partly shown in fig 10. This device could have its input bonded to one of two pads in order to obtain two functions with only one chip. The input is on (a) in the first case and on (b) in the second case. In the circuit of interest the input is on (a) and (b) is not used.

When the emitter (c) is kept at a low potential, (b) ends up at about the same level. The distance from the contact-hole (b) to the pnp-transistor (d) is only about 25 μ m and if moisture is present the potential can spread out and possibly turn on the transistor.

According to equation (2), the turn-on delay has a quadratic dependence on the distance x. Theoretically, the turn-on should be delayed by a factor 100 if the distance was increased from 25 μ m (b-d) to 250 μ m (c-d).

Comparative tests were carried out on components with and without this bond-opening. The result is presented in fig 11. As can be seen, the predicted delay by a factor 100 is not reached but the improvement (by a factor of 33 using the median value) is clearly shown.

PLASTIC ENCAPSULATION

Diffusion times for water through the bulk of the plastic in different environments were studied and the acceleration factor between 85C, 85% RH and 120C, 100% RH was determined.

Components without PSG

The turn-on time for the test chips in autoclave (120/100) was measured once a day for five days and the components in 85/85-test were monitored continuously for a period of 3 weeks. The applied bias was -80 V.

Components with PSG

It was difficult to obtain any results at all from devices covered with passivation. The conductivity is greatly reduced by the plastic and the inversion threshold voltage is higher for components with Vapox, so in order to get any results within reasonable time the applied voltage would have to be raised above the breakdown voltage of the diodes. The only component that could be measured had a turn-on time of 80 minutes.

Results

For the components in saturated autoclave, water reached the chip surface after a little more than one day. The time needed for those tested in 85/85 was about 3 weeks. This gives the acceleration factor A.

$$A = (21 \text{ days}) / (1.6 \text{ days}) = 13$$

In one case, the plastic seemed to have been displaced from the chip surface. This gave rise to an increase in sheet conductivity with a factor of 80.

SENSOR STABILITY

In order to check the reproducibility, the test chips were measured directly after removal of the lid and then remeasured (after 30 seconds, 30 minutes, 1 day and 3 days). It was concluded that 30 seconds was too short a time for the outspreading surface potential to relax, and this resulted in shorter and shorter turn-on times. Waiting for 30 minutes or 1 day between measurements gave satisfactory reproducibility. The values differed about 10-20%.

After 3 days the turn-on time for the chips kept at 12% RH was increased by a factor of 3 compared with the first measurements, while the turn-on time for those kept at room ambient did not change. This was somewhat unexpected and needed of more thorough examination.

Cerdips

Directly after removal of the lid, Cerdips were extremely sensitive to variations in relative humidity, but this sensitivity became less and less pronounced with time.

This "aging process" turned out to be strongly dependent upon humidity, i.e. storage in a dry atmosphere had an accelerating effect (fig 12).

A certain difference between chips with and without Vapox was noted in the sense that devices with Vapox tended to have a slower loss of sensitivity. This might be due to the hygroscopic nature of Vapox.

Metal cans

Devices encapsulated in metal cans seemed to be completely insensitive to moisture. They showed no tendency whatsoever to leakage. This experience was not new, the same behavior had been observed before in connection with other measurements /12/.

Washing for a few seconds in dilute HF (10 sec. 1% HF) restored the surface of the chip and the behavior was then the same as for Cerdips.

Why a dry atmosphere increases the contamination rate

The decrease in sensitivity is thought to be due to organic vapor in the air. These impurities make the surface hydrophobic, which means that condensed water molecules on the surface form small droplets instead of a continuous film, thus reducing the surface-charge spreading to a great extent.

Tamai et.al./13/ have studied the effect of water vapor on the contamination of metallic oxide surfaces, using the contact angle of water as a criterion for surface cleanliness. Their results show that the contamination rates of the clean surfaces are reduced by the coexisting water vapor (fig 13). This can be explained by the fact that the organic contamination is to be regarded as an adsorption process, and not just due to material "falling out" onto a surface /14/.

An oxide surface is often strongly hydrophilic, which implies that it has a preferential bonding to water. This in turn means that the organic contaminants should adsorb onto the surface competing with water molecules. Consequently, a dry atmosphere means "free access" to the adsorption sites.

The difference between cerdips and metal cans

Metal encapsulated chips appear to be insensitive to moisture, while those in Cerdips are very sensitive. This would mean that some step in the Cerdip encapsulation process radically affects the surface.

An efficient method for cleaning surfaces that have been exposed to organic vapor involves heating to 400-500 C in an oxidizing atmosphere. Cerdips are sealed in dry artificial air and the temperature during this process is around 450 C. The surface can thus be cleaned as a result of the sealing process /9/.

When sealing metal cans, the temperature is much lower and the atmosphere is non-oxidizing, so the surface is still contaminated after the

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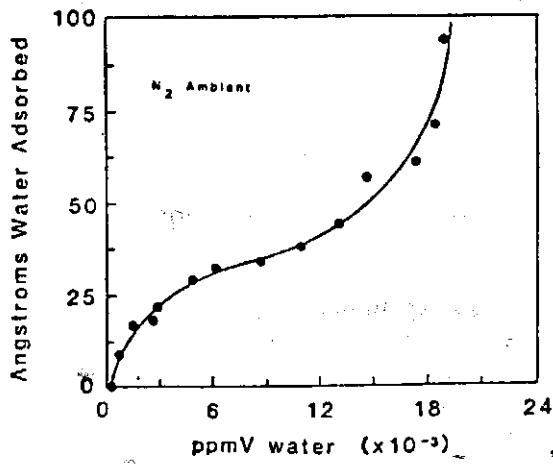


Figure 2 Water adsorption on SiO₂ /Ref 4/

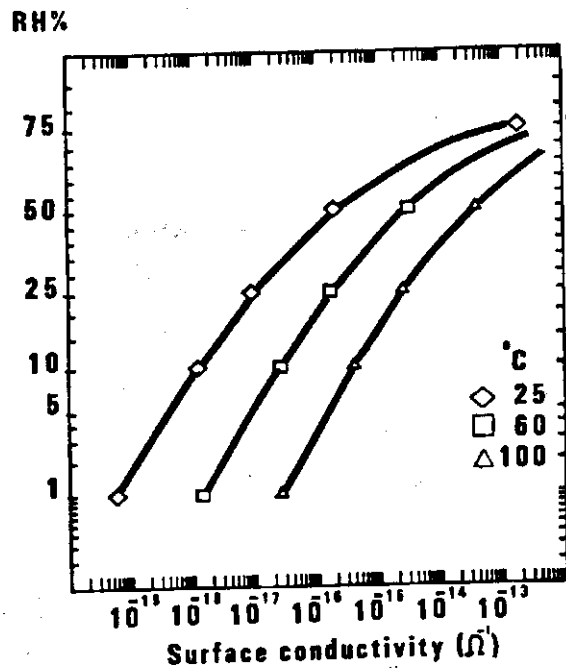


Figure 3 Calculated according to eqn (4)

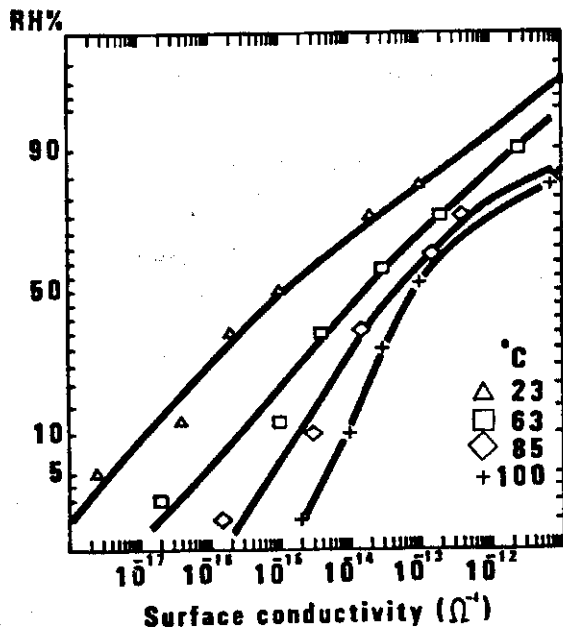


Figure 4 Data from Keelmans /6/

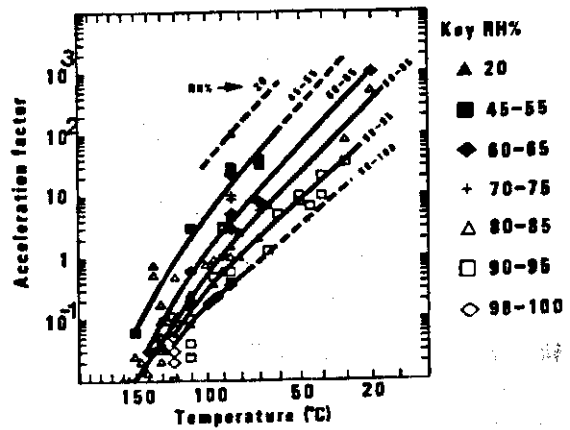


Figure 5 Corrosion acceleration factors from /5/ and other sources

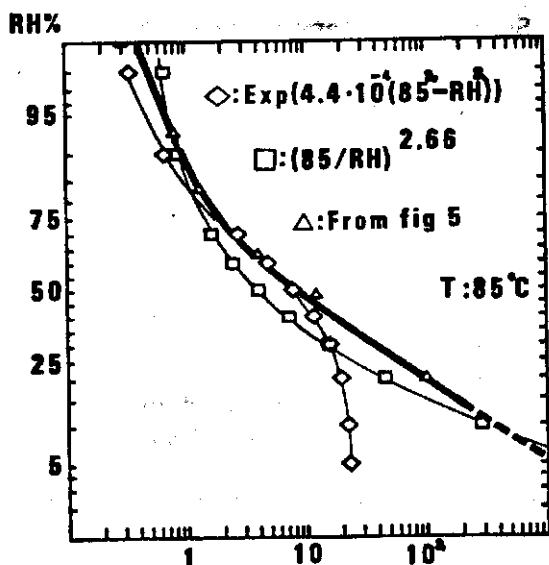


Figure 6 85%RH acceleration Different models

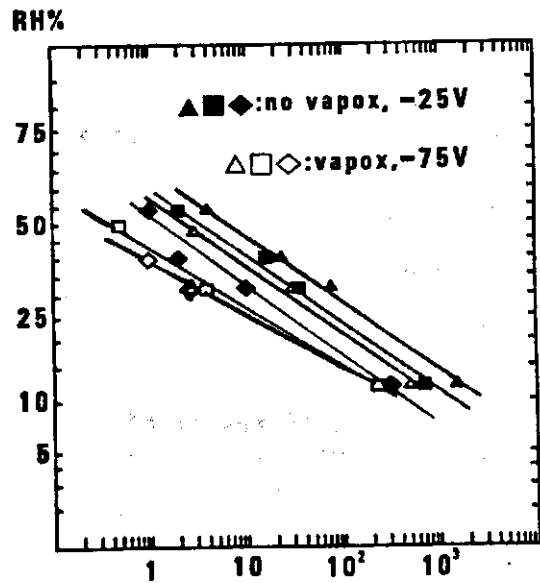


Figure 7 CST turn on time (s) vs RH

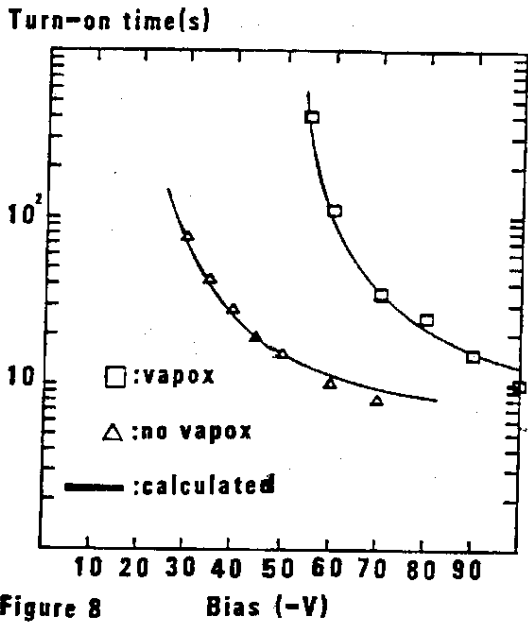


Figure 8 Turn-on time vs bias at 22C/12%RH

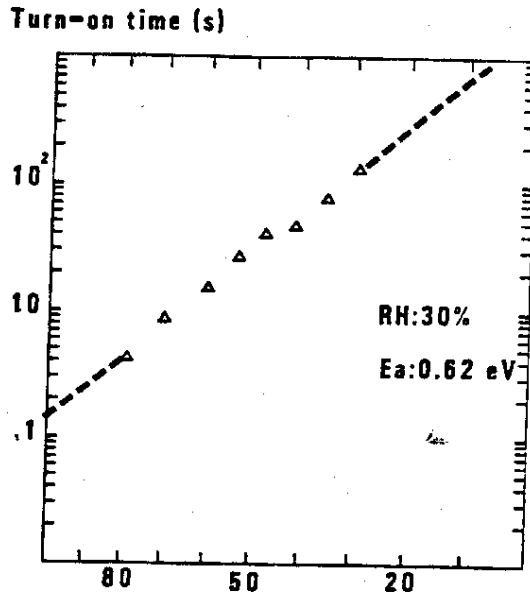


Figure 9 Temperature dependence of turn-on time

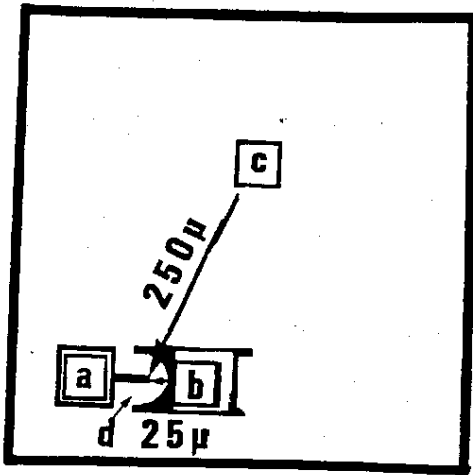


Figure 10 A pnp transistor with CST properties

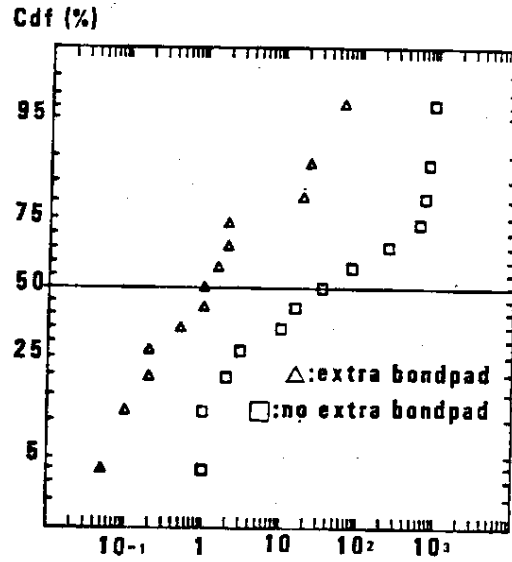


Figure 11 Distribution of values

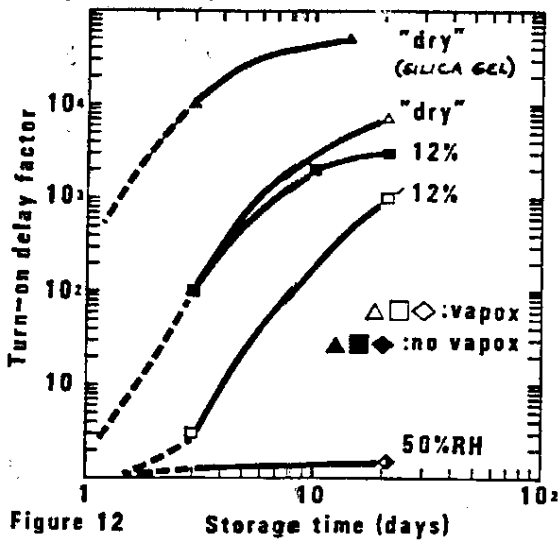


Figure 12 Loss of sensitivity at different ambients

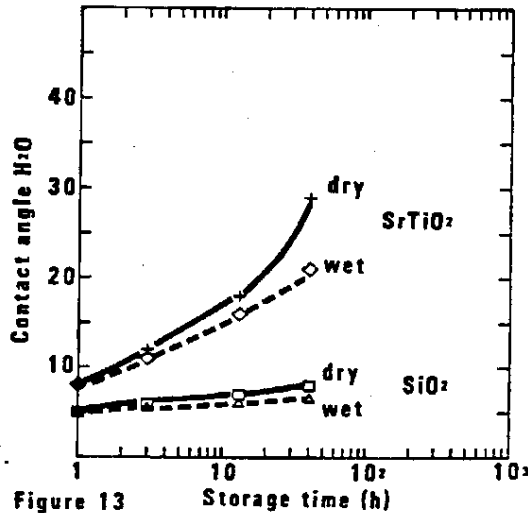


Figure 13 Change of contact angle by time. From ref /13/