

MODELING THE ANODIC CURRENT IN SILICON-GLASS BONDING

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Keywords: anodic bonding, glass polarization, ionic transport

ABSTRACT

We have constructed a model for the temporal evolution of the anodic space-charge layer and of the current during anodic bonding. The analytical expressions obtained interpolate continuously between the short-time and long-time behaviour of the current. The short-term behaviour corresponds to growth of a negatively charged, cation-depleted abrupt layer. We suppose that this layer grows until the electric field at the anode interface reaches a critical value, large enough to start pulling the less mobile negative ions towards the anode. We model this anion depleted layer as another abrupt layer, which is electrically neutral, and whose thickness also grows with time, keeping the electric field at the interface constant and equal to the critical value. These conditions completely specify a continuous solution for the whole time domain. We expect the results will be useful to the interpretation of experiments on glass-silicon anodic bonding.

INTRODUCTION

Anodic bonding was introduced by Wallis and Pomerantz [1] as a technique for joining metal to sodium-containing glass. Since then it has also been used intensively for silicon-to-glass bonding, and it is a useful technique in micromechanics, for cavity sealing, device encapsulation [2], and even for obtaining monocrystalline semiconductor thin films on top of amorphous glasses.

The metal, or semiconductor, is bonded to the glass by applying an external voltage with simultaneous heating, at temperatures compatible with microelectronic processing. The cathode makes contact with the glass, and the anode is the metal, or semiconductor. At the bonding temperature, the Na^+ sodium ions coming from the dissociation of NaO_2 , are mobile, and migrate towards the cathode, leaving behind the non-bridging oxygen ions (the oxygen ions bonded to only one silicon atom). Therefore a negatively charged depletion layer is formed adjacent to the anode. The electrostatic force between this negative layer and the positive charge induced on the anode brings the two sides into intimate contact. This force, allied to the softening of the glass, allows some accommodation of the glass to the opposing surface, making possible bonding between surfaces which are not perfectly planar.

The irreversible bond is formed by the oxidation of the conductor by reaction with oxygen ions at the interface.

The formation of an oxide layer at the interface has been observed [3]. On the basis of this bonding mechanism, the technique could in principle be applied to the joining of many other materials.

Anodic bonding is usually performed under constant temperature and voltage. The current can be measured during the bonding and used to monitor its progression. Models for anodic bonding should therefore predict the experimental behaviour of the current as a function of time. Carlson, Hang and Stockdale [4] have modeled the long-time behaviour of the current, and incorporated a field-dependent mobility for the ions in their model but assumed all of the voltage drop to be across the depletion layer of the glass. In the equivalent-circuit model proposed by Anthony [5], the depletion layer is replaced by a constant capacitance, resulting in an exponential decay of the current.

Albaugh [6] has pointed out that these models are not appropriate for the initial time period, when the voltage drop across the glass is due to its resistivity rather than to the capacitance of the depletion layer. He constructed a model that includes the correct boundary conditions for the initial time period, and obtained qualitative agreement with experimental current versus time curves. When his expressions are evaluated from the experimental material parameters, his model is in severe disagreement with the corresponding experimental results. We present an improved model, formulated in terms of the time evolution of cation and anion depletion layers in the glass. The analytic solution contains both the correct short-time behaviour obtained by Carlson and a long-term exponential decay of the current. The transition between the two regimes occurs when the field at the glass-metal interface reaches a value sufficient for anion drift.

MODEL

We consider the simplified model in which the potential is distributed wholly inside the glass. At $t=0$ (when the voltage is imposed on the pair), there is a uniform electric field along the glass, which tends to drag the Na^+ ions towards the cathode, here supposed to be on the left. The less mobile O^{2-} ions remain stationary. A region depleted of Na^+ is therefore formed adjacent to the anode. The charge density in this layer, which is in the region $-x_1 < x < 0$, is given by $-\rho_D = -Nq$, where q is the elementary charge and N is the original number of sodium ions per unit volume in the glass.

The electric field has its maximum value E_0 at the interface with the anode. As the thickness x_1 of the depletion layer increases, the electric field at the interface also increases. We suppose that at time $t=t_0$, the field at $x=0$ is intense enough to start dragging the less mobile oxygen ions towards the anode, where they are consumed in the oxidation reaction. We furthermore assume this is an abrupt transition, i.e., for $E < E_c$ (the critical field) the Na^+ -depleted layer is a perfect insulator, and at $E=E_c$ it is a perfect conductor. That is, for $E_0 < E_c$ the oxygen current is zero, and for $E_0 = E_c$ it takes the value necessary to keep the field at that value. This extreme form of nonlinearity is used to replace the exponential nonlinearity in the oxygen-current *versus* field characteristic, in order to allow an analytic solution.

The charge density and field distribution across the glass and the metal are shown schematically in Figure 1.

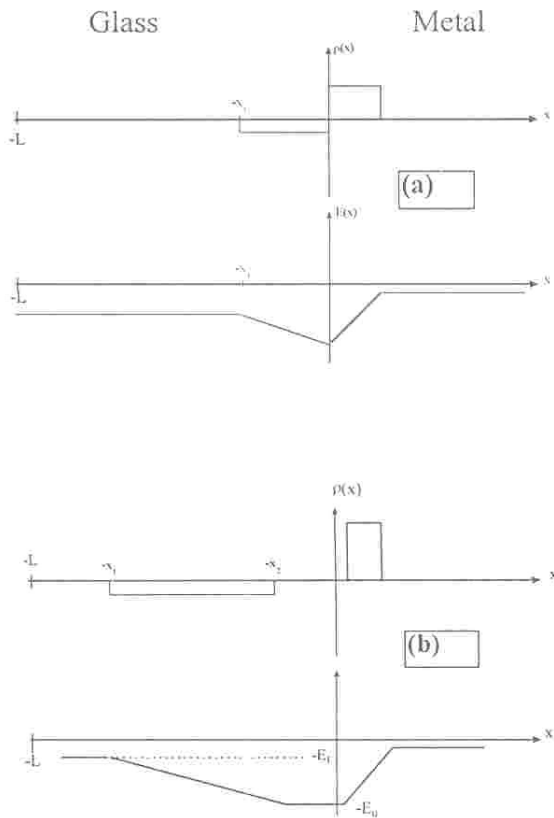


Fig. 1: Charge density and electric field distribution across the glass and the metal. (a): $t < t_0$, (b): $t > t_0$

The endpoints $-x_1$ and $-x_2$ of the charged layer then go on increasing, and an increasing fraction of the potential drop happens in the region $-x_1 < x < 0$. Correspondingly, the fraction of the potential drop to the left of $-x_1$ decreases accordingly, and so does the current, which goes to zero as $t \rightarrow \infty$. This decay turns out to be exponential and slower

than the one obtained by considering the Na^+ -depleted layer alone.

The potential drop in the glass is given by

$$V = V_D + V_R + V_N$$

where:

V_D = Potential drop in the charged layer ($-x_1 < x < -x_2$)

V_R = Resistive drop in the non-depleted glass ($x < -x_1$)

V_N = Potential drop in the neutral layer ($-x_2 < x < 0$),

The electric field is given by the Poisson equation in one dimension, supposing uniformity parallel to the interface, and the potential drop in each interval is obtained by integrating the electric field in that region.

The potential in each interval is given by:

$$V_D = - \int_{-x_1}^{-x_2} \left(-E_1 - \rho_D \frac{(x_1 + x)}{\epsilon \epsilon_0} \right) dx = E_1 (x_1 - x_2) + \rho_D \frac{(x_1 - x_2)^2}{2\epsilon \epsilon_0}$$

$$V_N = - \int_{-x_2}^0 (-E_0) dx = E_0 x_2$$

$$V_R = - \int_{-L}^{-x_1} (-E_1) dx = E_1 (L - x_1)$$

where ϵ_0 is the vacuum permittivity and ϵ is the dielectric constant of the glass. Therefore:

$$V = E_1 L + x_2 (E_0 - E_1) + \rho_D \frac{(x_1 - x_2)^2}{2\epsilon \epsilon_0}$$

and since

$$E_0 - E_1 = \rho_D \frac{(x_1 - x_2)}{\epsilon \epsilon_0} \quad (1)$$

we get

$$V = E_1 L + \rho_D \frac{(x_1^2 - x_2^2)}{2\epsilon \epsilon_0} \quad (2)$$

The continuity equation for the Na^+ ions relates the increase in time of x_1 with the Na^+ ionic current density J_1 , and a linearized current-field relation relates the latter to the electric field:

$$J_1 = -\rho_D \frac{dx_1}{dt} = -\frac{E_1}{r} \quad (3)$$

where r is the ionic resistivity for the Na^+ ions. Substituting the above for the field in equation (1) we get:

$$V = \rho_D r \frac{dx_1}{dt} L + \rho_D \frac{(x_1^2 - x_2^2)}{2\epsilon \epsilon_0} \quad (4)$$

Defining the characteristic length l_D and the characteristic time τ by:

$$V = \frac{\rho_D l_D^2}{2\epsilon\epsilon_0} \quad (5)$$

$$\frac{1}{\tau} = \frac{l_D}{2\epsilon\epsilon_0 r L} = \sqrt{\frac{V}{2\epsilon\epsilon_0 \rho_D}} \frac{1}{r L} \quad (6)$$

we can rewrite equation (3) as:

$$\frac{dx_1}{dt} = \frac{l_D}{\tau} \left(1 - \frac{(x_1^2 - x_2^2)}{l_D^2} \right) \quad (7)$$

and thus obtaining the differential equation for $x_1(t)$. The electric field at the interface is given by combining equations (1), (4) and (5):

$$E_0 = -E(x=0) = \frac{2V}{l_D} \left[\frac{(x_1 - x_2)}{l_D} - \frac{(x_1^2 - x_2^2 - l_D^2)}{2Ll_D} \right] \quad (8)$$

We can obtain the analytic solution of equation (7), both for $t < t_0$ and $t > t_0$. The current is obtained from equation (3):

For $t < t_0$, $x_2(t)=0$, and:

$$\frac{dx_1}{dt} = \frac{l_D}{\tau} \left(1 - \frac{x_1^2}{l_D^2} \right) = \frac{l_D}{\tau} - \frac{x_1^2}{l_D \tau}$$

$$x_1(t) = l_D \tanh\left(\frac{t}{\tau}\right)$$

and

$$J_1(t) = -\frac{\rho_D l_D^2}{\tau} \operatorname{sech}^2\left(\frac{t}{\tau}\right) = -\frac{V}{rL} \operatorname{sech}^2\left(\frac{t}{\tau}\right) \quad (9)$$

which are the same expressions obtained by Albaugh [6]. This behaviour cannot persist for long times. Keeping $x_2 = 0$ in equations (8) and (9) as $t \rightarrow \infty$ one gets:

$$x_1 \rightarrow l_D,$$

and

$$E_0 \rightarrow 2V / l_D.$$

For a numerical estimate, we use the same parameters as in Table I of Ref.[6]:

$$\begin{aligned} \epsilon &= 7 \\ \epsilon_0 &= 8.85 \cdot 10^{-12} \text{ J}^{-1} \text{ m}^{-1} \text{ C}^2 \\ V &= 1000 \text{ V} \end{aligned}$$

$$Nq = 2.77 \cdot 10^2 \text{ Cm}^{-2}$$

resulting in $l_D = 2.12 \cdot 10^{-6} \text{ cm}$, while Wallis [3] measured depletion lengths of the order of 10^{-3} cm , for these conditions. Also, the electric field would reach a value of $9 \cdot 10^8 \text{ V/cm}$, while the dielectric strength even of pure silica is of the order of 10^7 V/cm at room temperature and decreases with increasing temperature[7].

Before breakdown happens, the electric field at the interface causes the anions to start drifting towards the anode. We define the time at which this happens as t_0 , and use the assumption stated earlier: the oxygen current becomes equal to the sodium current and $x_1(t)-x_2(t)$ becomes a constant, which we call x_0 . Eliminating $x_2(t)$ in equation (7), we obtain:

For $t > t_0$,

$$\frac{dx_1}{dt} = \frac{l_D}{\tau} + \frac{x_0^2}{\tau l_D} - \frac{2x_0}{\tau l_D} x_1$$

whose solution, with the condition $x_1(t) = x_0$ is:

$$x_1(t) = \frac{1}{2} \left(x_0 + \frac{l_D^2}{x_0} \right) e^{-\frac{2x_0}{l_D} \left(\frac{t-t_0}{\tau} \right)} + \frac{1}{2} \left(x_0 + \frac{l_D^2}{x_0} \right)$$

The decay time is now:

$$\frac{1}{\tau'} = \frac{2x_0}{l_D \tau} = \frac{2}{\tau} \tanh\left(\frac{t_0}{\tau}\right) \quad (10)$$

and the current density is given by

$$J_1(t) = J_1(t_0) e^{-\left(\frac{t-t_0}{\tau'}\right)} \quad (11)$$

The parameter t_0 is uniquely determined by the value of the field E_0 at $t=t_0$. In this model this is the critical field needed to start the anion drift. Assuming $L \gg l_D$, we obtain from equation (8)

$$E_C = E_0(t=t_0) = \frac{2V}{l_D} \tanh\left(\frac{t_0}{\tau}\right) \quad (12)$$

RESULTS

In Figure 2 we show experimental points extracted from Fig.5 of Albaugh's article [6], for Si and 7740-glass anodic bonding, at temperature 290°C and $V=1000 \text{ Volts}$, together with curves calculated from the theoretical equations (9) and (10). Curve (1) is the result of a least-squares fit of our modified expression, with τ and t_0 as fitting parameters. The fitted values $\tau = 52.7 \text{ s}$ and $t_0 = 21.1 \text{ s}$ correspond to a t_0/τ ratio of 0.40 and a critical field $E_C = 3.4 \cdot 10^8 \text{ V cm}^{-1}$. Curve

(2) represents equation (9), with the same $\tau = 52.7$ s, and only follows the experimental results at short times, as noted by Albaugh. However, if one calculates τ from equation (6) using the experimental parameters $L=3.2$ mm and $r = 1.1 \cdot 10^7 \Omega\text{cm}$ (from Table I of Ref. 6), one gets $\tau = 3.14$ s.

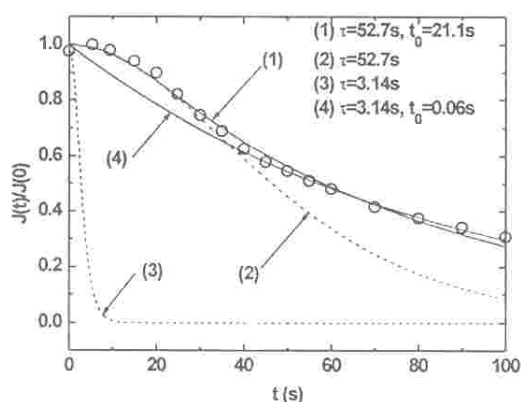


Fig.2 - Experimental current as a function of time, for 3.2 mm thick 7740 Pyrex to silicon bonding at 290°C [6] and curves calculated from equations (9) and (11), with choices of t_0 and τ as explained in the text.

With this value of τ there is no agreement at all between the experimental points and the unmodified Albaugh model. We find that keeping this value for τ and choosing $t_0 = 0.06$ s (corresponding to a t_0/τ ratio of 0.019 and a critical field $E_c = 1.8 \cdot 10^7 \text{ V cm}^{-1}$), we obtain good agreement for $t > 40$ s, but the wrong curvature for earlier times.

DISCUSSION

Using the available experimental parameters, we have not succeeded in obtaining quantitative agreement between the model and the experimental data. Our model does however, describe a continuous transition between the short term and long-term behaviour of the current.

Albaugh [6] has proposed that the causes for the quantitative disagreement between the apparent τ (of the order of 53 s in curves (1) and (2) of Fig.(2)) and the value calculated from equation (6) could found in the structural differences between the bulk glass and the depleted layer. In such case, we could claim our model to give very good agreement with the experiment. Our results show that agreement to Albaugh's model could not be expected anyway, since the current response is strongly affected by anion transport even for $t < \tau$.

In our model, the time constants τ and τ' in equations (9) and (11) are related to each other by equation (10). Therefore, a value of the phenomenological critical field E_c can be obtained from fits to small and large times, and its temperature dependence from fits to data from bonding at several temperatures. To proceed with these studies, we plan to use our own experimental data, since the details of the experimental conditions, and data spanning times from very small to vary large are often incomplete in the literature,

specially with respect to taking into account the effect of the spreading bonding front.

CONCLUSIONS

We have constructed a model for the time evolution of the anodic space-charge layer and of the current during anodic bonding. It is formulated in terms of the microscopic physics of the conduction rather than on equivalent circuit elements. We consider that the present approach has the merit of giving a unified picture for the whole process in terms of the appearance and growth of abrupt space-charge layers, and a single equation, namely equation (7). The nonlinearity of the anion conductivity is included, albeit in a very simplified form that allows for an analytic solution of the equations.

The treatment can be improved by replacing the model current-field relation by a more realistic one.

ACKNOWLEDGMENTS

This research is supported by Fapesp grant 95/1493-0. A.N.R and A.C.G are supported by Fapesp scholarships, and I.A.M. is supported by CNPq, DTI fellowship.

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