Conductance quantization in amorphous silicon switches

A. J. M. Neves and H. S. Moreira
Departamento de Física, Universidade Federal de Viçosa, 36.570-000 Viçosa-MG, Brazil
(Received 18 February 2004; revised manuscript received 3 September 2004; published 22 November 2004)

In order to establish whether or not there is conductance quantization in amorphous silicon switches, as has been accepted for thirteen years now, we have measured the current-voltage characteristics of these devices. The experiments were carried out in the temperature range from 4.2 K to room temperature. Although we have observed discontinuities in the characteristics, as reported by other authors, our statistical data analysis shows no evidence for conductance quantization with the quanta proposed in the literature, or with any other quantum one may come to suggest. Furthermore, it is shown that the data analysis presented in the literature is inappropriate to establish whether conductance quantization takes place in amorphous silicon. The statistical methods introduced here may be useful in other controversial problems to establish whether or not quantization occurs and also to determine the appropriate value for the related quantum.

DOI: 10.1103/PhysRevB.70.195333 PACS number(s): 73.40.Sx, 72.80.Ng

It has been known for almost fifty years[1] that many semiconductors, including silicon and some glass films have current-voltage characteristics $I(V)$ exhibiting a threshold voltage beyond which an attempt to change voltage further causes the current to jump steeply to a different value. This phenomenon has been called "switching" and its long history can be traced back to Tyler in 1954.[2] It is consensual that switching stems from the formation of a highly conductive filament. For a comprehensive review of the studies in this field see Barnett.[1] More recently Hajto *et al.*[3,4] have published results on *p*-type amorphous silicon films sandwiched between metallic contacts showing $I(V)$ curves with multiple current jumps. The authors suggested that the conductance $G=I/V$ at the top (higher current part) and/or at the bottom (lower current part) of these jumps was quantized in a manner reminiscent of the quantization observed in quantum point contacts,[5,6] that is, $G=(2e^2/h)N$, where N is an integer. The phenomenon was first observed at temperatures up to 190 K. Later it was found to take place even above room temperature.[7,8] Furthermore the application of a magnetic field of 0.2 T, oriented at 30° with the current filament joining the metallic contacts, would split the current jumps producing additional jumps corresponding to conductance quantization in units of e^2/h. It was also suggested that the conductance at the jumps should, even in the absence of a magnetic field, be an "integer or a half integer multiple" of $2e^2/h$. This is equivalent to accept a conductance quantum with half the original value. These observations have been confirmed independently by other groups[7,9] and extended to other material systems.[10] It was once proposed that the conductance quantum should effectively be a quarter of the value established originally and also that the measured resistance at the jumps should be corrected for a series resistance in order to observe conductance quantization.[11] These latter results seem to have been long surpassed since all subsequent publications on amorphous silicon, including those from the same authors, refer only to the quantum $2e^2/h$ or e^2/h and do not mention any correction to the experimental data.[9,12–15]

Conductance quantization in amorphous silicon would undoubtedly be a remarkable phenomenon. Despite the theoretical effort to understand it,[4,9,12–14] the phenomenon remains to be clearly explained. The model proposed is based on the assumption that there is ballistic transport of charge in the silicon layer. However it is difficult to understand how it could happen above room temperature and out of the linear regime. At any rate, this paper is not concerned with theory. It intends to establish from the experimental facts whether or not conductance quantization actually occurs in amorphous silicon devices. The statistical methods employed here are reminiscent of earlier attempts in this direction that have not reached the mainstream of science.[11,16]

In this paper we study amorphous silicon switches exactly like those described above. Although our data contain discontinuities in the $I(V)$ characteristics as seen before, a careful statistical analysis shows no evidence for quantization with any quantum above the experimental precision, at any temperature from 4.2 K to room temperature, with or without correction for a parasitic series or parallel resistance.

The samples employed in this work consist of a 1000 Å thick layer of amorphous silicon sandwiched between two metal contacts—one made of chromium and the other of vanadium. The active part of the device is an *a*-Si cylinder with 10 μm diameter and 1000 Å height. The devices were prepared and electrically conditioned as described in the literature.[3,4] The semiconductor film was grown by rf-glow discharge decomposition of SiH_4 containing 10^4 ppm of B_2H_6.

Figure 1 presents the $I(V)$ characteristics of one of the samples at 4.2 K, with no magnetic field applied. The curve was obtained by measuring the current through the device while sweeping the voltage up and down. Although the overall features of the $I(V)$ characteristics are the same for all devices which exhibit current jumps, the number of jumps, their size, and the voltage at which they occur vary considerably from device to device. The data from a single device are normally stable and reproducible over periods of a few hours, or even a few days, although occasionally sudden changes occur which result in a completely different set of $I(V)$ characteristics. These changes appear to be more fre-

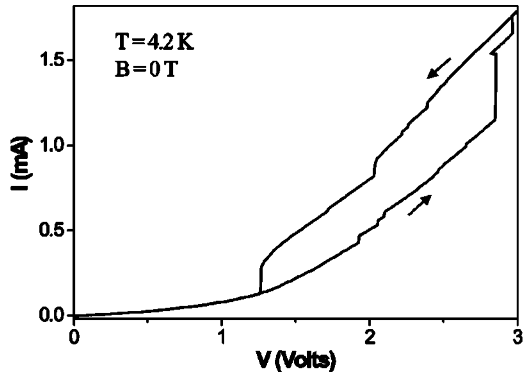

FIG. 1. $I(V)$ characteristics obtained at 4.2 K, in the absence of magnetic field. The arrows indicate the direction of the voltage sweep.

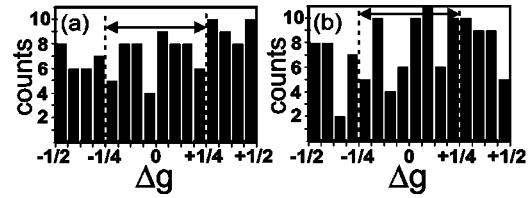

FIG. 2. Histograms of the deviation of the dimensionless conductance $g=G/(2e^2/h)$ from the closest integer. Part (a) refers to the tops of current jumps and part (b) to the bottoms.

quent in a noisy electrical environment. We have observed that devices which have $I(V)$ curves with only a single, large ($\sim$0.3 mA) current jump are particularly stable and may remain unchanged for longer periods. Note that in the curve shown in Fig. 1, the number of steps and their position depends on whether the voltage is swept up or down. This hysteresis has been observed in all samples which show steps. The aforementioned quantization is supposed to happen preferentially in down sweeps.[3,7]

Here we assess the claim that the conductance at current jumps is quantized in units of $2e^2/h$, e^2/h, or $e^2/(2h)$, that is to say, $G=(2e^2/h)N$, $G=(e^2/h)N$, or $G=e^2/(2h)N$, where N is an integer. It is important to construct a strict and objective criterion for quantization. Hajto *et al.*[3,4] considered the conductance to be quantized as long as the measured resistance was within a few percent off a quantized value (6% for $N<7$). This is not a restrictive criterion. For example, any jump occurring between the quantized values $5(2e^2/h) = (2581\ \Omega)^{-1}$ and $6(2e^2/h)=(2151\ \Omega)^{-1}$ has its resistance at most 215 Ω off a quantized resistance value. This means only 8% off. Hence, any resistance measured between $N=5$ and $N=6$ will be from 0 to 8%, on average 4%, off a quantized value, irrespectively of the underlying physical phenomenon. Similarly, any resistance measured between $N=4$ and $N=5$, between $N=3$ and $N=4$, and between $N=2$ and $N=3$, will be on average 5, 7, and 9% off a quantized value. Therefore, it is not surprising that most of the measured resistance values lie within a few percent off some quantized value. If one is prepared to accept a smaller conductance quantum (e.g., e^2/h), any set of measurements will be even closer to quantized values.

In order to provide a fairer test to the claims of quantization, we have carried out a statistical analysis of the conductance at the high (top) and low (bottom) current points of the jumps seen in the $I(V)$ curves of several samples in the temperature range from 4.2 K to room temperature. The data consist of 120 jumps obtained with 29 devices. The conductance $G=I/V$ at the top and bottom of each jump was expressed as a dimensionless conductance defined by $g=G/(2e^2/h)$. If G were actually quantized in units of $2e^2/h$, one would expect the data points to gather around integer values of g. Figure 2 shows histograms of the deviation Δg of the dimensionless conductance to the closest integer, both for the tops [Fig. 2(a)] and bottoms [Fig. 2(b)] of current jumps. The vertical coordinate (counts) related to each of the 16 regions in which the horizontal axis was divided in represents the number of data points with Δg in that region. For example, a jump whose measured conductance was $(2500\ \Omega)^{-1}$ would correspond to $g=5.16$ and would contribute with one count in the region which contains the point $\Delta g=0.16$. The value of the dimensionless conductance g in the data set varies from 0.1 to 24. If quantization actually took place, one would expect a distribution of Δg with a peak at $\Delta g=0$. However, the distribution obtained from the experimental results (Fig. 2) resembles a uniform distribution, which is consistent with randomly distributed conductance values. In order to do a quantitative test for conductance quantization, the Δg axis was split into two equal-length regions; one extends from $-\frac{1}{4}$ to $+\frac{1}{4}$ (indicated by the arrows in Fig. 2) and the other comprises the rest of the Δg axis. Let us name the former region the "quantized region" and the latter the "nonquantized region." If quantization occurred, one would expect that more experimental points would lie within the quantized region than out of it. The experimental data show that only 56 tops (47% of the total) and 62 bottoms (52%) lie within the quantized region. This distribution indicates that there is no evidence for quantization in units of $(2e^2/h)$. Similar analyses for conductance quantization in units of e^2/h and $e^2/(2h)$ were carried out defining, in one case, $g=G/(e^2/h)$ and $g=G/[(e^2/h)/2]$ in the other. In the former case it is found that 61 (51%) tops and also 61 (51%) bottoms lie in the central region. In the other case 59 (49%) of the tops and 61 (51%) of the bottoms are in the quantized region. These results are consistent with the 50% in the quantized region expected for a random distribution. We conclude, therefore, that there is no experimental evidence for conductance quantization in units of $(2e^2/h)$, (e^2/h), or $e^2/(2h)$. It is important to point out that there is no data selection here. In fact, we have included in this statistical analysis all reproducible jumps of all samples in both up and down voltage sweeps. If conduction quantization actually happens in a meaningful set of devices, it should show up, even if the phenomenon does not take place in some other devices, jumps or sweeps.

As mentioned before, the current jumps were first supposed to occur at conductance values of $(2e^2/h)N$, with integer N. Then half integer values were also allowed, meaning quantization with half the original quantum. Of course, any set of data will be as close as wanted to quantized values, if one is allowed to make the quantum sufficiently small. The

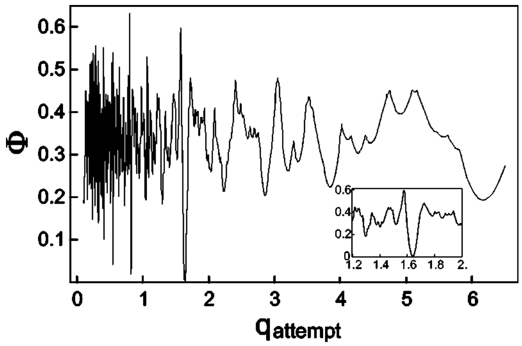

FIG. 3. Dependence of Φ on the guess for the charge quantum. The inset shows in greater detail the global minimum around $q_{\text{attempt}}=1.6$.

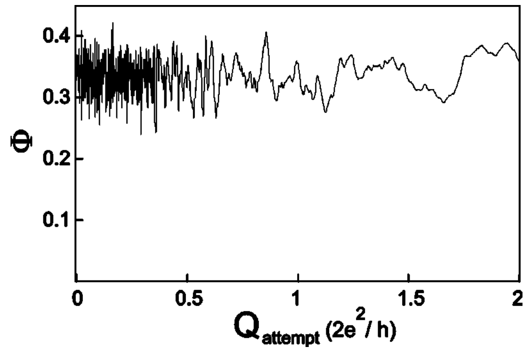

FIG. 4. Dependence of Φ for the top of the jumps on the guess for the conductance quantum in units of $2e^2/h$.

statistical method used above does not allow this freedom, since the quantized and nonquantized regions have the same length, whatever the proposed quantum. It seems relevant to wonder whether the conductance at jumps is quantized with some other quantum one may propose. A way to address this question can be set forth considering the problem of charge quantization and the data from Millikan's oil drop experiment. Here are the charges (in units of 10^{-19} C) of nine oil drops taken from a textbook: 6.563, 8.204, 11.50, 13.13, 16.48, 18.08, 19.71, 22.89, and 26.13. If we step into Robert Millikan's shoes, our problem is the following. All these measured charges (q_i, i from 1 to 9) are approximately an integer multiple of a certain unknown quantum "e." What is the value of e? A computational approach is to define a function (Φ) that qualifies a guess (q_{attempt}) for the quantum and then try all acceptable guesses. We want the function $\Phi(q_{\text{attempt}})$ to have a small value if q_{attempt} is a good guess, that is, if all the drop's charges (q_i) divided by q_{attempt} are close to an integer. The function below, where p is the number of charges measured and $R(x)$ is the integer closest to x, is the quadratic deviation of q_i/q_{attempt} to the closest integer. It is easy to see that Φ has lower values for better guesses. If there were no experimental errors, a perfect guess, $q_{\text{attempt}}=e$, would render $\Phi=0$. Due to the normalization factor $4/p$, the maximum possible value for Φ is 1:

$$\Phi(q_{\text{attempt}}) = \frac{4}{p}\sum_{i=1}^{p}\left[\frac{q_i}{q_{\text{attempt}}} - R\left(\frac{q_i}{q_{\text{attempt}}}\right)\right]^2.$$

Of course, the value of e can be at most equal to the charge of the drop with the lowest measured charge (6.563). Figure 3 shows a plot of Φ for q_{attempt} ranging from the experimental precision (0.001) to 7. The function oscillates wildly and drops down almost to 0 at $q_{\text{attempt}}=1.6$, the actual electron charge. Of course there are other minima at $1.6/N$, where N is an integer. With some thought, one can convince himself that the value of e has to be the highest q_{attempt} value that minimizes Φ, that is, 1.6. This method was applied to the conductance measured at the current jumps. Figure 4 shows a plot of Φ for the top of the jumps as a function of the guess for the conductance quantum (Q_{attempt}) in units of $2e^2/h$. The function has no clear global minimum and never comes below 0.2, which is the minimum value for Φ one obtains with a set of data generated randomly. The corresponding plot for the bottom of the jump has the same features. This shows that conductance quantization is not present in our data, with any quantum.

As mentioned before, it was once proposed that the resistance measured at jumps should be corrected for a series resistance in order to reveal the quantized values.[11] Conductance quantization in amorphous silicon was established without this correction[3] and it has not been used in the literature, except for the aforementioned publication. Nevertheless this proposal is discussed here for completeness. For each silicon switch, the authors tried several values for the series resistance and chose the one which brought the measured jump resistances closer to the quantized values. This fitted resistance was then subtracted from the measured values. The procedure resulted in a Δg distribution which, unlike the authors' uncorrected data and our own measurements (Fig. 2), has a Gaussian shape with a peak at $\Delta g=0$. The peak at this position was regarded as a proof of conductance quantization. This is not necessarily the case. The data processing described here is a parameter fitting, not the duly correction for a well-known series resistance. Therefore, this procedure obviously has to take the measured conductances closer to the quantized values, or to any other target values one may choose. The key point is to determine whether the series resistance correction brings the measured jump conductances closer to the quantized value than it would bring a set of random numbers.

Of course, it is conceivable that the devices may have a considerable nonquantized resistance in series with the proposed quantized conductance channel. Considering the existence of a current filament surrounded by a less conductive region, which underlies switching,[1] it is even more plausible to have some "parasitic" resistance in parallel with the supposedly quantized channel. The following procedure was carried out to investigated whether a correction of our data for a voltage-independent series or parallel resistance would uncover the proposed quantized conductance. First, for each of the 29 devices employed, a series resistance was fitted to bring the corrected jump resistances (measured values minus fitted series resistance) as close as possible to the quantized values. This parameter fitting was accomplished trying all series resistances, from zero up to the lowest jump resistance measured for the device, in 5 Ω steps. For each of these trial

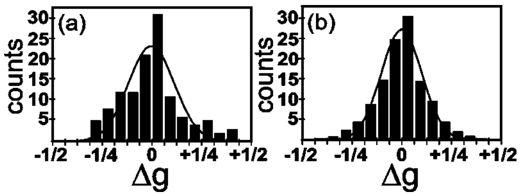

FIG. 5. Histograms of the deviation of the series resistance corrected dimensionless conductance $g=G/(2e^2/h)$ from the closest integer. Part (a) refers to the bottom of current jumps and part (b) to the collections of random numbers.

resistances, we corrected the conductance at the jumps and used these corrected values to calculate the corresponding dimensionless conductance (as before, $g=G_{\text{corrected}}/G_{\text{quantum}}$, where $G_{\text{quantum}}=2e^2/h$). Then, we calculated the Φ function based on the definition above, where the q_i are substituted by the corrected g values of the device and q_{attempt} is replaced with G_{quantum}. The series resistance fitted for a device is the one which gives the lowest value for Φ. Figure 5(a) shows the Δg distribution obtained with the corrected conductance at the bottom of the 120 jumps in our data. In contrast with the uniform distribution related to the uncorrected data (Fig. 2), this distribution resembles a Gaussian peaked at $\Delta g=0$, whose width at half height is 0.27. This peak is not necessarily evidence for conductance quantization. After all, 29 parameters (one series resistance for each switch) were fitted, aiming to peak the distribution at this point. The width of this distribution is a measure of how close the corrected measured conductances are from the quantized values. In order to decide whether the silicon switches have a quantized conductance channel in series with some other resistance, we have generated 29 sets of random numbers. Each random set mimics the results from one device, in the sense that it contains one number for each jump observed in the $I(V)$ curve of the device and this number was randomly picked in the range from the minimum to maximum jump conductance measured with that device. Correcting each random set for a fitted series resistance and calculating g, the way described above, one obtains a Gaussian-like distribution peaked at $\Delta g=0$. One hundred collections of 29 random sets were generated and processed as described. All of the 100 distributions had a width close to the one obtained with the corrected experimental data. In fact, summing up these distributions and dividing by 100, one obtains the average Δg distribution of random numbers corrected for series resistances which is shown in Fig. 5(b). It is a Gaussian and its half-height width (0.24 ± 0.03) is essentially the same as that of the distribution obtained with the corrected experimental data (0.27) shown in Fig. 5(a). The tolerance mentioned (0.03) is the average absolute deviation of the width of the random collections to their average width, which turns out to be the width of the average Δg distribution. In other words, the series resistance correction brings the experimental jump conductances closer to the quantized values, but similar sets of random numbers are brought just as close. Naturally, there is no ground to claim there is a quantized conductance channel concealed by some series resistance, unless the distribution corresponding to the corrected experimental data is considerably narrower than the one associated with randomly generated numbers. Therefore, our data show the conductance at the bottom of the jumps is not quantized in units of $2e^2/h$, even if a series resistance correction is applied. The same procedure was carried out with the conductance measured at the top of the jumps. The width of Δg distribution related to the corrected experimental values is 0.22, also giving no support for the claim of conductance quantization.

We have also examined whether our data corrected for a series resistance would support conductance quantization with the other quantum values proposed so far, i.e., e^2/h and $(e^2/h)/2$. This was carried out as described above, but recasting the dimensionless conductance as $g=G_{\text{corrected}}/G_{\text{quantum}}$, with $G_{\text{quantum}}=e^2/h$, and later $G_{\text{quantum}}=(e^2/h)/2$. For the former tentative quantum (e^2/h), the width of the Δg distribution for the corrected experimental data is 0.22 for the bottoms of the jumps and 0.20 for the tops. The width of the corresponding average distribution of corrected random numbers is 0.23 ± 0.03. Using the latter tentative quantum, the distribution widths were 0.24, 0.22, and 0.23 ± 0.02 for the bottom of the jumps, for the tops, and for the corrected random numbers, respectively. Once again, there is clearly no support for the claim of conductance quantization.

On the same lines described above, we have corrected our data to account for a possible resistance in parallel with a quantized conductance channel. A parallel resistance was fitted to each device. This was carried out trying all values from the highest measured jump resistance up to 300 $k\Omega$, in 100 Ω steps. Trying a lower resistance would not make sense, since the parallel resistance ought to be higher than the measured value. On the other hand, trying higher values would be irrelevant, since the correction becomes rather small, if the parallel resistance is much higher than the measured jump resistance, which is typically in the 10^3 Ω range. As before, the fitted resistance for a device is the one which gives the lowest value for Φ, that is, the one which brings the corrected conductances closer to the quantized values. For the bottom of the jumps, using the tentative G_{quantum} in turns equal to $2e^2/h$, e^2/h, and $(e^2/h)/2$, we obtained Gaussian-like distributions peaked at $\Delta g=0$, whose width at half height were 0.57, 0.60, and 0.49, respectively. For the tops, using G_{quantum} $2e^2/h$, e^2/h, and $(e^2/h)/2$, the width of the Δg distributions were 0.59, 0.55, and 0.58, respectively. After the parallel resistance correction, the aforementioned random collections gave rise to Δg distributions whose width were 0.55 ± 0.04, 0.54 ± 0.04, and 0.55 ± 0.03, for tentative conductance quantums equal to $2e^2/h$, e^2/h, and $(e^2/h)/2$, respectively. Once more, one cannot credibly propose the conductance at jumps is quantized.

It is noticeable that the width of the Δg distribution related to the corrected experimental data is roughly the same, whichever is the tentative quantum. This scale invariance is consistent with randomly distributed g values. It is also important to emphasize that we have only tried corrections for voltage-independent parasitic resistances. Therefore one could argue that the parasitic resistance may depend on the voltage bias applied to the device. Nevertheless, we feel that without a supporting theory, the proposition that quantization actually takes place, but is concealed by a resistance with an unknown dependence on voltage, would be a matter of faith.

We have studied silicon switches like those supposed to exhibit conductance quantization. Although the samples displayed current jumps in the $I(V)$ curves as those presented in the literature, a careful statistical analysis of the data showed no evidence for conductance quantization with any quantum above the experimental precision. It is also shown that the data analysis previously used in the literature is inappropriate to establish whether conductance quantization occurs in amorphous silicon. We believe the subject could be further enlightened, if other authors analyzed their data using the statistical methods proposed here. The method employed to prove that conductance is not quantized with any quantum can be useful in other problems to look for a possible quantum for the measured quantity.

This work is supported by FAPEMIG (Brazil). The authors acknowledge useful discussions with Professor P. C. Main and Professor L. Eaves.

[1] A. M. Barnett, *Injection Phenomena*, Vol. 6 of *Semiconductors and Semimetals*, edited by R. K. Willardson and A. C. Beer (Academic Press, New York, 1970).

[2] W. W. Tyler, Phys. Rev. **96**, 226 (1954).

[3] J. Hajto, A. E. Owen, S. M. Gage, A. J. Snell, P. G. LeComber, and M. J. Rose, Phys. Rev. Lett. **66**, 1918 (1991).

[4] J. Hajto, A. E. Owen, A. J. Snell, P. G. LeComber, and M. J. Rose, Philos. Mag. B **63**, 349 (1991).

[5] B. J. van Wees, H. van Houten, C. W. J. Beenakker, J. G. Williamson, L. P. Kouwenhoven, D. van der Marel, and C. T. Foxon, Phys. Rev. Lett. **60**, 848 (1988).

[6] D. A. Wharan, T. J. Thornton, R. Newbury, M. Pepper, H. Ahmed, J. E. F. Frost, D. G. Hasko, D. G. Peacock, D. A. Ritchie, and G. A. C. Jones, J. Phys. C **21**, L209 (1988).

[7] M. Jafar and D. Haneman, Phys. Rev. B **47**, 10 911 (1993).

[8] J. Hajto, M. J. Rose, A. J. Snell, I. S. Osborne, A. E. Owen, and P. G. LeComber, J. Non-Cryst. Solids **137&138**, 499 (1991).

[9] M. Jafar and D. Haneman, Phys. Rev. B **50**, 5707 (1994).

[10] Eui-Jung Yun, M. F. Becker, and R. M. Walser, Appl. Phys. Lett. **63**, 2493 (1993).

[11] J. Hajto, A. J. Snell, M. J. Rose, A. E. Owen, I. S. Osborne, T. Kosa, A. Holmes, and R. A. G. Gibson, *Proceedings of the MRS Spring Meeting*, MRS Symposia Proceedings No. 297 (Materials Research Society, Warrendale, PA, 1993).

[12] J. Hajto, B. McAuley, A. J. Snell, and A. E. Owen, J. Non-Cryst. Solids **198–200**, 825 (1996).

[13] J. Hajto, B. McAuley, A. J. Snell, G. H. W. Milburn, and A. E. Owen, Appl. Surf. Sci. **92**, 579 (1996).

[14] J. Hajto, B. Joo, B. J. Pendleton, and A. E. Owen, J. Non-Cryst. Solids **227–230**, 1182 (1998).

[15] J. Hajto, J. Hu, A. J. Snell, K. Turvey, and M. Rose, J. Non-Cryst. Solids **266–269**, 1058 (2000).

[16] A. J. M. Neves, Ph.D. thesis, Nottingham University, 1993.