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On the origin of the electrical activity in silicon grain boundaries

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Résumé. — Les joints de grains dans le silicium sont des pièges pour les porteurs de charge des deux types. Cette activité électrique est reliée à la présence de niveaux profonds dans la bande interdite, qui peuvent être d'origine chimique et *extrinsèque* ou structurale et *intrinsèque*. Les connaissances actuelles sur les joints plans symétriques, entièrement reconstruits, impliquent une origine *extrinsèque* pour ces niveaux. Cependant la détection de liaisons pendantes dans les joints généraux indique qu'une origine *intrinsèque* de l'activité électrique reste possible.

Abstract. — Grain boundaries in silicon are traps for both types of charge carriers. This electrical activity is related to deep levels in the forbidden energy gap, which may have two origins : chemical and *extrinsic* or structural and *intrinsic*. Present knowledge on planar symmetric grain boundaries, which are fully reconstructed, induces an *extrinsic* origin of these levels. However, dangling bonds detected in general grain boundaries indicate that an *intrinsic* origin of the electrical activity is still possible.

1. Introduction.

Polycrystalline semiconductors are used in device technology in two opposite directions : either as passive components with specific properties due to the presence of the grain boundaries, either as active components, despite these same properties [1-8]. In the first category, one may find baryum titanate capacitors, zinc oxyde varistors and polycrystalline silicon interconnections ; in the second are situated bulk poly-Si solar cells and thin-film poly-Si field effect transistors. The films are particularly interesting to develop 3-D integrated circuits [9-15].

Research on polycrystalline semiconductors has much developed during the last ten years, very often with help from governments through the solar cell programs (e.g. Action de recherche concertée « Silicium polycristallin »). It has been the object of dedicated conferences in 1981 [1], 1982 [2] and 1984 [3]. A Summer School has been held on the subject in 1984 in Erice (Italy). The book of this School [4] is certainly the most detailed in the smallest form to tackle this theme. Recent reviews by Mataré [5-6], Grovenor [7] and Seager [8] are also available on the subject. Grovenor is the most complete and presents very clearly the metallurgical side of the problem. As the charge carrier transport

at GB is well developed in these works it is not going to be presented here. The reader interested in the subject will particularly report to Seager (transport perpendicular to the GB plane) [8] and to Mataré (transport along the GB plane) [5-6].

Taylor *et al.* proposed in 1952 [16] a model of the energy bands and states at grain boundaries (GBs), which is now universally admitted. The 2-D disordered zone at GB induces the existence of electronic states in the forbidden band gap. The states trap the majority carriers on the one hand (electrons in a n-type semiconductor), thus creating a potential barrier at GB and a depleted zone in the neighbouring grains (see Fig. 1), which are respectively the origin of resistance and capacitance effects very usefull for instance in semiconducting ceramics [9-11]. On the other hand, these states are attractive and recombination centres for the minority carriers (holes in the same material), lowering the efficiency of poly-Si solar cells [12].

There are two ways for the GB disordered zones to create gap states : either with the *intrinsic* crystallographic mismatch, either because of the *extrinsic* presence of segregated defects or impurities. Among the large amount of experimental studies performed on the subject [1-8], only a few permit the direct

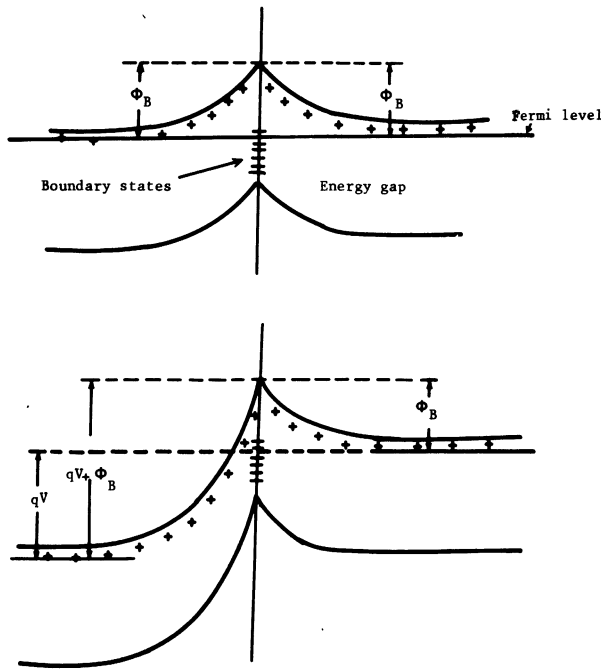


Fig. 1. — Gap states and band bending at GB, as postulated by Taylor *et al.* [16]. Above : zero-bias condition. Below : the applied bias induces a potential drop V at GB.

correlations between structure and electrical activity of GBs. In this review, the emphasis is put on results obtained on bulk large grained polycrystalline semiconductors or on bicrystals, where the origin of the GB electrical activity can be determined.

2. Electrical activity of grain boundaries.

2.1 STATES IN THE FORBIDDEN GAP. — The kind and density of states detected depend much on the technique which is used. However many means provide the necessary data, a complete review of which is made in [7]. They include majority carrier trap density measurements, recombination centre density measurements, and paramagnetic centre (dangling bond) detection.

The majority carrier trap density may be inferred from I - V dc curves interpretation [7, 17] or more directly from ac admittance spectroscopy [18] and capacitance transient spectroscopy (deep level transient spectroscopy, DLTS) [19]. While the GB densities of states obtained through I - V curves or admittance spectroscopy are continuous, with various shapes depending mostly on the studied material, DLTS of bicrystals, made by Broniatowski using GB capacitance, shows on the contrary discrete densities of states in Ge [19] and Si [20] depending on the annealing treatments.

States which serve to the recombination of electron-hole pairs without being majority carrier traps have not been studied quantitatively in silicon grain

boundaries. However numerous experiments have been performed on the recombination force of the GBs, which are of prior interest for the solar-cell materials. These experiments are described in the next chapter.

The density of paramagnetic centres is known through electron spin resonance (ESR) experiments. Classical ESR have been performed on polycrystalline silicon, the « dangling bond » signal (with Landé factor $g = 2.0055$), well known in amorphous silicon, is generally found [21]. However Ballutaud *et al.* [22] recently detected a new related ESR signal ($g = 2.0084$) more sensible to hydrogenation (hydrogen : see Sect. 5). Lenahan and Schubert [23] made spin resonance experiments on bicrystals, detected by voltage measurements across the GBs, which they called spin dependent trapping (SDT). It allowed a detection sensibility ($\approx 10^8$ centres) three orders of magnitude better than standard ESR [24]. Moreover, it permitted to assert that trivalent silicon centres (« dangling bonds ») detected in polycrystals are indeed situated at GBs and that they are the basis of the GB potential barriers.

All the techniques mentioned obtain between 10^{11} to 10^{14} GB states cm^{-2} , the most common value being 10^{12} cm^{-2} . The average distance between two electrically active centres in a GB is therefore around 10 nm (i.e. : 30 interatomic distances). Moreover, the average planar density in silicon being approximately equal to $1.5 \times 10^{15} \text{ cm}^{-2}$, this also means that around one thousandth of the atoms at GB induce detectable states.

2.2 RECOMBINATION OF ELECTRON-HOLE PAIRS. —

The recombination of electron-hole pairs is directly linked to the presence of deep levels [25]. This part of the electrical activity is observable when minority carriers are injected into the material. Local injection, which permits the local characterization lacking in the transport experiments, is possible with illumination by focused light or electron beams. This is the basis of light and electron beam induced current methods (LBIC and EBIC). They consist in observing the local variations in the photo- (or electro-) voltaic effect. An example of EBIC micrograph is shown in figure 2. The samples must be diodes, the recombining GBs lower the induced current, and they appear dark on the EBIC or LBIC images. This contrast has been modelled by Zook [26], Donolato [27] and Marek [28], the theory gives access to the recombination velocity at a given GB, s_{GB} defined by [26] :

$$s_{\text{GB}} = \frac{J_{\text{mc}}}{N_{\text{mc}}}$$

where J_{mc} is the recombination flux at GB (minority carriers per unit area of GB and per second) and



Fig. 2. — Scanning electron microscopy micrograph. Interpenetrated secondary electron (above) and EBIC (below) images, showing the different electrical activities of various GBs. The grain orientations giving the Σ -values are deduced from electron channelling patterns.

N_{mc} is the local concentration of excess minority carriers, s_{GB} has the dimension of a speed. Sundaresan *et al.* [29] showed that s_{GB} actually depended on the injection level. Therefore, it cannot be used as an absolute characterizing parameter, however these authors included this dependence in a model and could infer the GB density of states from EBIC profiles.

One may also measure the photo- (or electro-) conductivity enhancement when the beam crosses the GB. Indeed, the barrier height is lowered by illumination, due to the neutralization of the trapped majority carriers by the photo- (or electro-) generated minority carriers, its value (ϕ_B) has thus been deduced from light spot scanning photoconductance: $\phi_B = 0.3\text{--}0.4$ eV in cast polycrystalline silicon [30-31], in good agreement with the values obtained in majority carrier transport experiments ($\phi_B \approx 0.5$ eV) [7-8].

The induced current methods detect the electron-hole pairs which do not recombine. The luminescence methods, which detect the radiative recombinations, also allow to localize the non radiative recombination centres (e.g. GBs). Scanning photoluminescence (SPL) and cathodoluminescence (CL), which give defect contrast very similar to EBIC's [32], are however delicate to use in polycrystalline indirect-gap semiconductor characterization (e.g. : Si), since the luminescence yield is very low.

The spatial resolution of all these methods is a key parameter when structure-property correlations are needed, since GB microstructure is not continuous

at a very fine scale (see next sections). New methods to enhance both spatial resolution and structure-property correlations are thus being developed using transmission electron microscopy (TEM, STEBIC) (see Sect. 4).

3. Structure.

3.1 THE MODELS. — The first way to model GB structures has been to use bulk dislocations [33]. It is indeed possible to built all the GBs, on the model of the subgrain boundaries, with arrays of very close dislocation lines. This representation led to the fruitful early work of Hornstra [34] who first proposed core structure models for special symmetric « tilt » boundaries in diamond-like crystals. Some of Hornstra's structures are still now acknowledged after the TEM work performed during the last decade. The designation of the GBs made great progress with the generalized use of the concept of coincidence. This was first introduced by Friedel in 1926 [35] but was only developed recently [36-38]. The coincidence site lattice (CSL) is made with the atomic sites common to both grains (where the two crystals would coincide if they interpenetrated). A given CSL is designed by its Σ -index, which is the reciprocal density of sites in coincidence. GBs with low Σ -values can be associated with simple dislocation structures. The most recent models [39-41] present these dislocations as made with 3-D structural Units (SUs), one SU being associated with one simple structure GB (e.g. a low Σ -GB). Only a few of these SUs would be needed to rebuilt any GB in a given material. At the present time, this model leads to total reconstruction of dangling bonds in all the $\langle 110 \rangle$ tilt boundaries considered [41]. It is however necessary to specify that this result is valid for the diamond structure of single element semiconductors on the one hand [42, 43], and for symmetric boundaries with no defects on the other hand. General GBs are not symmetric and their plane is often not defined. Their structure can only be described in terms of steps at the atomic scale, which steps may be loci for dangling bonds or segregated impurities.

The extrinsic GB dislocations are at last worth to be mentioned. They are originally bulk dislocations, often dissociated in the GBs [44], and their stress fields are not relaxed (which is not the case for intrinsic dislocations), making them strong attractors for segregation (see Sect. 5).

3.2 THE EXPERIMENTAL IMAGES. — To make GB experimental images, only a few means are possible. Classical experiments in surface structure characterization are not possible here since GBs are difficult to break at the interface, seducing methods like tunneling microscopy are thus prohibited.

The crystallographic orientation relationships between the two adjacent crystals may be obtained from various X-ray or electron diffraction methods, but the only means to image and quite completely analyse the grain boundaries are the different sorts of transmission electron microscopy (TEM). Four kinds of structural characterizations may be performed in TEM :

— High Energy Electron Diffraction (HEED), where the periodic structure of coherent GBs makes extra diffraction spots [45] ;

— Convergent Beam Electron Diffraction (CBED), which may give rigid body displacements in addition to the bicrystal space group direct characterization [46] ;

— Conventional TEM (CTEM), where the rigid body displacements are measured through the « α » fringe method [47] and ;

— High Resolution Electron Microscopy (HREM), where the atomic columns are resolved [48].

The stress is put here on HREM where the most spectacular results have been obtained. This method has first been used for GB characterization in semiconductors by Krivanek *et al.* [49] who performed structure images of $\Sigma = 3$ and $\Sigma = 9$ in Ge. This kind of GBs, taken from polycrystals, were then also imaged by other workers [50]. However the most systematic work on GB HREM structure has been made on specially grown bicrystals [51-53]. The work of Bourret *et al.* on the subject [48, 51, 53-55] is certainly the most outstanding since it methodically covers the different orientation relationships modelled by Hornstra [34] about the $\langle 110 \rangle$ and $\langle 100 \rangle$ axes. This way of proceeding may be called « the Grenoble School », it contains both the growing of nearly defect-free Ge and Si bicrystals and their characterization in TEM (HREM and HEED). Moreover, the bicrystals are then dispatched to other laboratories for corroborated electrical measurements (see Sect. 4). The image shown here (Fig. 3) comes from this work. It presents a first order twin ($\Sigma = 3$) with steps containing both the $\{112\}$ plane (I) (dominating here but less common in the nature), and the $\{111\}$ usual twin plane (II). The $\{112\}$ interface is less coherent than the $\{111\}$, it is thus often called (improperly) « incoherent », it also induces a rigid body translation from the exact coincidence position to relax the atomic positions at the interface [47, 54-57]. Due to its complicated core structure associated to a simple CSL, this interface has been widely investigated : while Hornstra's model presented a high density of dangling bonds [34], while a more recent model built on energy considerations [58] also led to the same result, though with a different atomic arrangement, HREM images allowed Bourret *et*

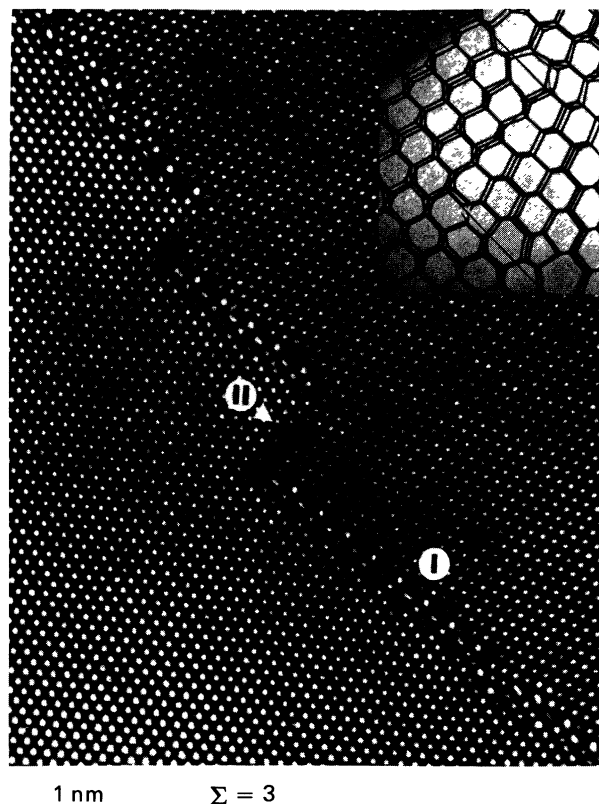


Fig. 3. — High resolution electron microscopy image of a first order twin in Ge, with $\{112\}$ (I) and $\{111\}$ (II) twin planes. The rigid body translation necessary to accommodate the $\{112\}$ interface is clearly visible in the $\langle 111 \rangle$ direction. The picture shows that the GB structure strongly depends on the local orientation of the GB plane. However, in the case of this twin, reconstruction is always possible. An enlarged view of the steps surrounding zone II is shown in the inset [54, 55] (Courtesy of A. Bourret).

al. [57] to conclude that there was finally no dangling bond at all.

The general conclusions of the combined HREM and other TEM studies are that there exist SUs with no dangling bond, that permit total reconstruction of all the *symmetric* GBs studied [41].

4. Relationships between electrical activity and structure.

4.1 INDIRECT EXPERIMENTAL CORRELATION. — The indirect correlations between electrical activity and structure of GBs mostly come from the works made on bicrystal ingots, electrical measurements being performed on given samples and structure characterization being obtained from other samples from the same ingot. This method allows to derive corroboration of the *average* electrical and structural properties. It has successfully been applied on the bicrystals grown in Grenoble, on which have been

performed DLTS [19-20], EBIC [59] and combined EBIC and I - V measurements [67].

Without previous anneal, the low- Σ studied bicrystals show no electrical activity, whereas the low angle bicrystals (with high Σ) exhibit a low density of gap states [18, 19]. This density (10^{11} cm^{-2} in Si with misorientation angle $\theta = 7.8^\circ$ [18], and 10^9 cm^{-2} in Ge with $\theta = 3.5^\circ$ [19] is found in fact too low to correspond to the intrinsic dislocation structure, but is associated to extrinsic dislocations [18] or to oxyde precipitates [61]. The only GBs to show important activity without heat treatments are general GBs [63-65].

However, short anneals at 750°C (2 h) [59, 62] of the low- Σ bicrystals, as well as longer anneals at 450°C (24 h) [62] and POCl_3 treatment at 850°C (30 min) [63], can make them electrically active. Broniatowski found in DLTS discrete deep levels associated to such anneals, related to precipitation. Corroboration with micro-analytical scanning transmission electron microscopy (STEM) is in progress [20], it is a first evidence of an *extrinsic* origin of the GB associated deep levels.

4.2 COMPUTER SIMULATION. — As the low- Σ GBs have no dangling bond on the one hand (see Sect. 3) and no electrical activity on the other hand, computer simulations have been carried out, to check the presence of gap states that would come from the distorted bonds [66]. Two structures have been studied : the relatively simple $\{221\}$ $\Sigma = 9$ [67, 68] and the more complex $\{112\}$ « incoherent » $\Sigma = 3$ [69]. Using slightly different methods, the three authors found indeed no gap state associated to these structures in Si. As other symmetric GBs show no electrical activity (if not annealed), the result might also be valid in their cases. Electrical activity would therefore be an *extrinsic* phenomenon in *symmetric* GBs.

4.3 DIRECT EXPERIMENTAL CORRELATION. — In parallel with the bicrystals studies, experiments were carried out on large grained Si polycrystals for solar cells, with both electrical and structural characterization performed on the same zone of the same GB. The possible means include LBIC or EBIC on the one hand and TEM on the other hand [64, 70-76]. This kind of investigations permitted to establish, in silicon, that general GBs and subgrain boundaries are more active than coherent (low- Σ) ones [70-72], and that the $\{111\}$ $\Sigma = 3$ twin is not active, unless it is decorated [64, 71-74]. Moreover, Silvain could associate the electrical activity of sub-GBs to given types of dislocations [75], while Dianteill and Rocher could show that the electrical activity, in the $\Sigma = 9$ twin, depended strongly on the GB plane orientation, varying from 0 for the twin plane to a maximum for a random plane [76].

A great difficulty in these experiments is linked to the delicate procedure, in which the samples have to be thinned to electron transparency without losing the important zones. Attempts are therefore made to short-circuit this procedure : either by performing structural characterization by means of electron channelling patterns (ECPs) in the scanning electron microscope (SEM) simultaneously with EBIC, either by achieving EBIC directly on the thinned sample in the TEM-STEM (STEBIC) [65, 77]. In the first solution, the spatial resolution is poor ($10 \mu\text{m}$), and the GB planes are difficult to infer from the ECPs [65] ; however, it gives important indications in simple cases : it showed for instance that in a $\Sigma = 3$ boundary containing the two possible twin planes ($\{111\}$ and $\{112\}$), the electrical activity did not come from the « incoherent » $\{112\}$ plane, but from the edges of the steps [77]. In other respects, STEBIC is very promising (Fig. 4), since it offers a high resolution (up to $0.1 \mu\text{m}$), in addition to its *in situ* character [65].

With the direct experimental correlations, the importance of crystallographic parameters appears : the grain boundary electrical activity changes with the *coincidence index*, and changes with the *boundary plane orientation*.

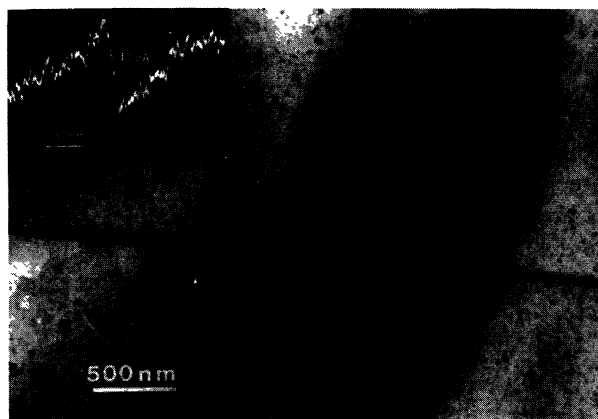


Fig. 4. — TEM image and STEBIC profile at a stacking fault in silicon. The small grained contrast is due to the Al film of the thin Schottky diode and the horizontal black line is the contaminated track of the STEBIC profile shown in the inset [65] (Courtesy of C. Cabanel and J. Y. Laval).

5. Foreign atom segregation.

Segregation may be an equilibrium process with foreign atoms strictly located at GB planes. It is then obtained by long anneals, and it is more important at low temperature, since it is mostly based on elastic energy differences between bulk and GB-sites. Segregation may also be a non-equilibrium

phenomenon, where the impurity concentration is not only enhanced in the core of the defect, but also in its surroundings. In this case it may be found in as-grown materials. Precipitation occurs in both cases when the local solid solubility limit is overpassed. All these aspects were acutely developed by Aucouturier in [4]. In semiconductors, the segregation processes modify the electrical properties of the GBs. This was first evidenced by Paulus in ferrites, who noticed enhanced resistivity at GBs due to metallic ion segregation, by means of combined microresistivity measurements and autoradiography [78]. In conventional semiconductors (e.g. : Si) there are two types of foreign atoms regarding their electrical activity in the bulk : dopant atoms in substitutional sites on the one hand and other impurity atoms on the other hand. Their segregation to GBs will have indeed different electrical consequences.

5.1 DOPANT SEGREGATION. — Dopant segregation is since a long time considered as an important factor in the specific high resistivity found in polycrystalline semiconductor thin films (segregated atoms being supposed to be electrically inactive) [79]. This has been checked only recently. Thus, with resistivity data obtained on carefully annealed Si samples Mandurah *et al.* could show that As and P indeed segregated to GBs, but B did not [79]. In other respects, Rose and Gronsky obtained the first direct evidence of equilibrium segregation for P in Si GBs, by means of energy dispersive X-ray microanalysis (EDX) in STEM [80]. Grovenor *et al.* [81] and Wong *et al.* [82] then used successfully EDX to detect quantitatively the equilibrium segregation of As at Si GBs. These authors additionally correlated the EDX results with resistivity measurements : in the case of their highly doped material, segregation increased the resistivity far more than if it was only due to the lack of electrically active dopant, As atoms at GBs obviously enhanced the GB specific resistivity [82]. All column III acceptors in Si do not follow the behaviour of B. Indeed, the segregation of Al has been detected in unannealed polycrystalline Si by EDX [83] (Fig. 5), and, simultaneously with oxygen, by Auger electron spectroscopy (AES) and secondary ion mass spectroscopy (SIMS) performed on fractured GBs [84]. In this last case, the correlation with EBIC profiles and barrier height measurements showed that Al presence enhances the electrical activity of GBs in the unannealed material, but lowers it after short anneals (20 min) at 900 °C, as compared with only B-doped similarly treated materials [84]. This point is very interesting since other authors found a passivation effect of the GBs by Al diffusion at low temperature (≈ 400 °C) [85, 86]. Al-O complexes have been suspected to be at the origin of the activation [64],

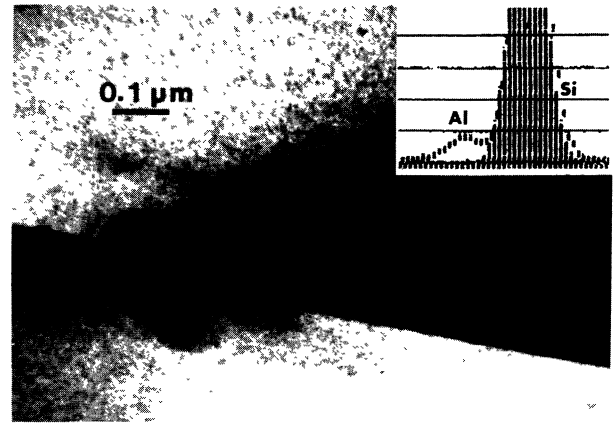


Fig. 5. — TEM image and EDX spectra (inset) of a grain boundary in Al doped polycrystalline silicon, showing Al segregation. The spectrum recorded in the matrix (vertical black lines, no Al signal) is superimposed to the one recorded on the GB (dotted line, Al signal). The 0.3 μm wide dark area on the GB is the contamination spot due to the analysis.

while the passivation seems to be due to Al alone. However, if the GB dangling bonds are the origin of the electrical activity in Si, all dopants could be passivating agents if segregated in the right sites, since they all have (by definition) an unpaired electron.

5.2 OTHER IMPURITIES. — Mainly two types of non-doping impurities have received attention : the passivating impurities (Cu, H), and the ones with high concentration in solar-grade material (O, C).

Cu diffusion at 400-500 °C passivates the GBs, and it also enhances the bulk minority carrier diffusion length [86]. H implantation or diffusion is widely used to passivate not only the grain boundary but also the bulk recombination centres [22, 87, 88]. Its action was first understood to be simple dangling bond saturation, it now seems to be manifold. There is sometimes a finite life-time of this passivation under illumination [89], which indeed depends on the passivated site, this phenomenon has to be compared to what is well known in hydrogenated amorphous silicon as the « Staebler-Wronski » effect [90].

Carbon and oxygen are introduced in solar grade silicon during the growth processes, in amounts attaining the solid solubility limits (respectively $3 \times 10^{17} \text{ cm}^{-3}$ and $3 \times 10^{18} \text{ cm}^{-3}$ at melting point [91, 92]. In other respects their behaviours are already known in single crystal Si : donor creation at 400-500 °C and precipitation at higher temperature associated with O, and catalytic effect of O and C on the other's precipitation [93]. Their segregation to grain boundaries has been observed and it enhances the GB electrical activity. Rallon *et al.* performed

combined EBIC and autoradiography in the « ribbon-against-drop » (RAD) material (grown on a graphite film), they indeed found ^{14}C segregation to GBs and twin boundaries, and showed that the latter have electrical activity linked with C presence [94]. Oxygen in other respects, has been detected at Si GBs by Kazmerski and Russel, by SIMS and AES, before and after annealing [84]. Its presence is well correlated with the decrease of minority carrier life time and the increase of barrier height. The active segregated oxygen may moreover be passivated by hydrogenation [95].

This chapter makes clear that impurity presence *changes* the GB electrical activity. Therefore an « impure » material will very likely have grain boundaries with *extrinsic* electrical activity.

5.3 PRECIPITATES. — Carbon and oxygen have also been found under precipitated form : SiC precipitates were observed in GBs in TEM [73, 96] ; and oxygen was found by electron energy loss spectroscopy (EELS), in decorated $\Sigma = 3$ twins in unannealed Si [64], and in Ge, at the sub-GB dislocation cores [97]. An electrical activity was linked with the oxyde precipitates : the decorated twin was recombining [64], and the sub-GB in Ge showed deep levels in DLTS [19].

These last results on the importance of precipitation are confirmed by the works on the low- Σ symmetric bicrystals [20, 59], where electrical activity is also due to precipitates.

In more general GBs lastly, precipitation also occurs at electrically active interfaces [72]. The presence of nano-precipitates, not easily detectable in conventional TEM, is moreover very probable [77]. Precipitates could therefore also induce electrical activity in general GBs.

Finally, when no active structural unit has yet been designed to explain either intrinsic or extrinsic electrical activity, precipitation is, up to now, the only characterized cause of deep levels at GB.

6. Conclusion.

The numerous studies performed on grain boundaries in semiconductors, aiming at the comprehension of their electrical activity, lead to the following statements :

1) Planar symmetric grain boundaries have reconstructed structures, introducing no gap states. Their electrical activity is entirely of *extrinsic* origin, it has been related to the presence of precipitates.

2) General grain boundaries contain dangling bonds detected by electron spin resonance, however their activity is also dependent on impurity content. The structural units around the dangling bonds are not known.

It is therefore possible to summarize the future work needed as follows :

1) Regarding the impurity influence, it is necessary to develop the understanding of impurity *segregation* and *diffusion* at GB, since it already appears that it is possible to *design* the GB electrical activity by those means.

2) Regarding the dangling bond detection, it will be interesting to associate a given GB microstructure to the ESR signal. It will then be possible to conclude on the intrinsic GB electrical activity.

On the application side also, opportunities are now changing. The polycrystalline silicon solar cell programs well sustained the research during the last years. But the GB studies are now less important for solar cells since GBs, in the present bulk materials used in this industry, are fewer and of simple structure. On the contrary all microcrystalline materials must be focused on since their applications, as mentioned in introduction, are wide. The thin film technology is continuously developing, with in particular new structures using the piling up of the films. Such a pile-up is shown in figure 6 [98]. GBs in these structures deserve to be studied with the fundamental knowledge now accumulated on these defects.



Fig. 6. — Cross sectional TEM view of two superposed polycrystalline silicon films both grown on the thermal oxide of the preceding layer. The picture shows that surface roughness is kept very low and that important grain growth is obtained by thermal treatment (Courtesy of C. d'Anterrosches).

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