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CURRENT FILAMENT FORMATION IN GOLD COMPENSATED SILICON PIN DIODES

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Abstract

In semiconducting materials with current controlled negative differential conductivity an inhomogeneous current density distribution can arise leading to a well-defined spatial pattern in the form of current filaments. Detailed experiments are performed on silicon pin diodes showing a pronounced multistability in the current voltage characteristics. By using the voltage contrast and the electron beam induced voltage (EBIV) methods in a SEM, it is confirmed that each jump in the current is accompanied with the formation or disappearance of a well defined transverse electrical structure between the two contacts as a result of a current filament. This non-uniform state of the material is found to exhibit a clear solitary structure. The observed voltage oscillations are traced back to instabilities of this spatial structure.

KEY WORDS: Voltage Contrast, Electron Beam Induced Voltage, Silicon, pin Diodes, Negative Differential Conductivity, Multistability, Instability, Pattern Formation, Current Filaments, Nonlinear Dynamics

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Introduction

It is well known that a negative differential conductivity can lead to an electrically non-uniform state in a semiconducting material when an external voltage or current is applied. The resulting spatial structures which can be stable or unstable are a direct consequence of a true bulk property, to be clearly distinguished from a boundary type negative resistance as in the famous Esaki diode, cf. /14/. Two special kinds of electrical inhomogeneities can be observed. A voltage controlled negative differential conductivity can lead to the formation of electric field domains which are utilized to generate microwave signals in the well known Gunn diodes. On the other hand, a current controlled negative differential conductivity can produce a filamentary current density distribution.

Due to the technical significance of the behaviour of the Gunn domains, a large amount of literature has been published dealing with the generation and motion of the electric field domains, for example in GaAs. In particular, the voltage contrast method in a conventional scanning electron microscope (SEM) has been applied as a special two-dimensional tool to study the propagation of these domain walls /8/, showing the dynamic steady state features of this kind of spatial structure. On the other hand, a correspondingly systematic treatment of the case of an S-shaped current density electric field characteristic is still lacking. Mostly, this situation of current filament formation has been treated only as to be the dual case with respect to the field domains /14, 17/. On the other hand experimental results have pointed out that inhomogeneous current distribution can be observed in semiconductor diodes /2/ . But up to now there is no clear evidence for what a filament really is, for example concerning its size and structure especially along the direction of current flow. Only a preliminary experimental result on a filament in VO_2 has been published where also the SEM has been used to get a two-dimensional picture /3/. Very recently, extensive theoretical work has been done on the behaviour of current filaments /15, 16/, where the questions of the solitary behaviour and the problem of stability have also been treated. Detailed experimental results are needed.

In this paper, the pattern formation due to current filaments in Au compensated silicon pin diodes /4, 5, 11/ is studied where special emphasis is laid upon the two-dimensional spatial structure in the material between the contacts. Since the filamentary current density is expected to be associated with a well-defined inhomogeneity of the electric field /15, 16/, the voltage contrast and the EBIV methods in a SEM are used to get an immediate picture of the corresponding potential distribution on the surface of the sample parallel to the current flow /10, 13/. It is shown that this method gives an easy way to study the pattern formation in these diodes to be attributed to the different states of the current voltage characteristic. The result of the qualitative SEM experiments are compared with quantitative measurements by using a potential probe. Finally, instabilities as detected by oscillations of the external voltage are also examined and traced back to instabilities of the spatial structure.

Au compensated silicon pin diodes

The pin diodes are fabricated by a two step diffusion process where n-type silicon wafers (20 - 30 Ω cm) are used as starting material. Firstly, a thin layer of Au is deposited on one side of the cleaned and polished silicon wafer. The following Au diffusion is carried out at 950 °C for 2h. Secondly, after removing the remaining Au layer an n layer and a p layer are formed on the two sides respectively by boron and phosphorous diffusion for 4h at 950 °C. The donator and acceptor densities in these layers with thicknesses of about 0.5 µm are larger than $5 \cdot 10^{17}$ cm^{-3}. Finally Al is evaporated on both sides to form the metallic contacts. Sandwich diodes are cut out of the wafer as can be seen in the inset of Fig. 1. The four semiconductor surfaces are finally polished. During the measurements the samples are fixed between two aluminium mounting blocks for a better handling and to establish good cooling conditions. A typical current voltage characteristic of such Au compensated silicon pin diodes is shown in Fig. 1. Clearly, several interlocking hysteresis cycles can be observed leading to a pronounced multistability, i. e., several current values can be achieved at the same voltage level. The dotted lines mark the observed jumps, the slope being determined by the impedance of the current source.

Two-dimensional voltage contrast and EBIV measurements

The samples are mounted in the specimen chamber of the SEM. Fig. 2 shows the basic set-up. Via a series resistance R the sample is connected to an external voltage supply to bias the diode in forward direction. An additional source connected to ground can supply an offset voltage. As can be seen from the circuit diagram, two experimental methods are provided in a usual way in order to get images of the diode surface between the contacts, i. e. the qualitative voltage contrast and the electron beam induced voltage (EBIV) methods. Employing the voltage contrast method, a more linear relation between the signal of the SE detector and the local potential on the diode surface is obtained when the n contact was set to an offset of +10 V with respect to the surrounding ground potential. It should be noted that in the following photographs of the voltage contrast mode an additional topography contrast is always superimposed. The sensitivity of the EBIV method has been increased by chopping the electron beam and using the conventional lock-in technique. The electron energy was chosen to be 2 keV at a beam current of about 10^{-10} A. It has been found that the influence of the electron beam on the electrical behaviour of the pin diode with the beam parameters as specified above is negligible.

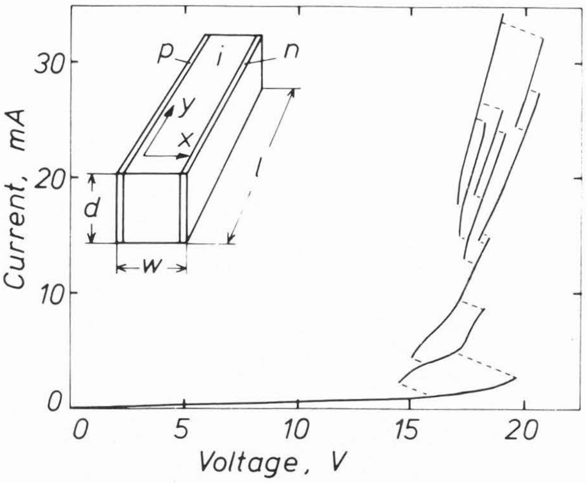

Fig. 1: Typical forward current voltage characteristic of a pin diode.
The inset shows the schematic structure of the diodes. Typical dimensions:
l = 1...5 mm, w = 230...280 µm, d = 200...300 µm

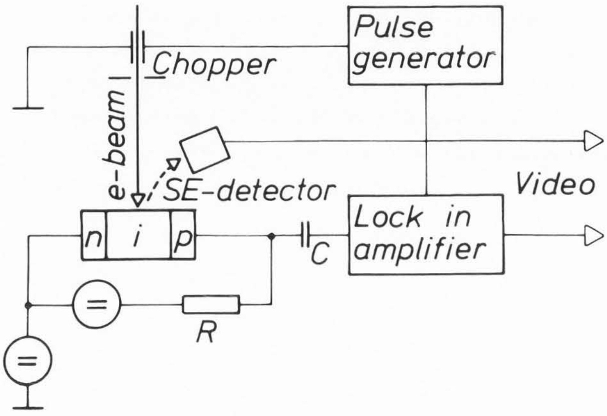

Fig. 2: Circuit diagram for the voltage contrast and the EBIV method.

Experimental results

The following illustrations show in general the top x-y-plane of the pin diodes as sketched in Fig. 1. In the photographs of Fig. 3 the potential distribution of the diode can be seen where the operating point is just beyond the first jump in the current voltage characteristic.

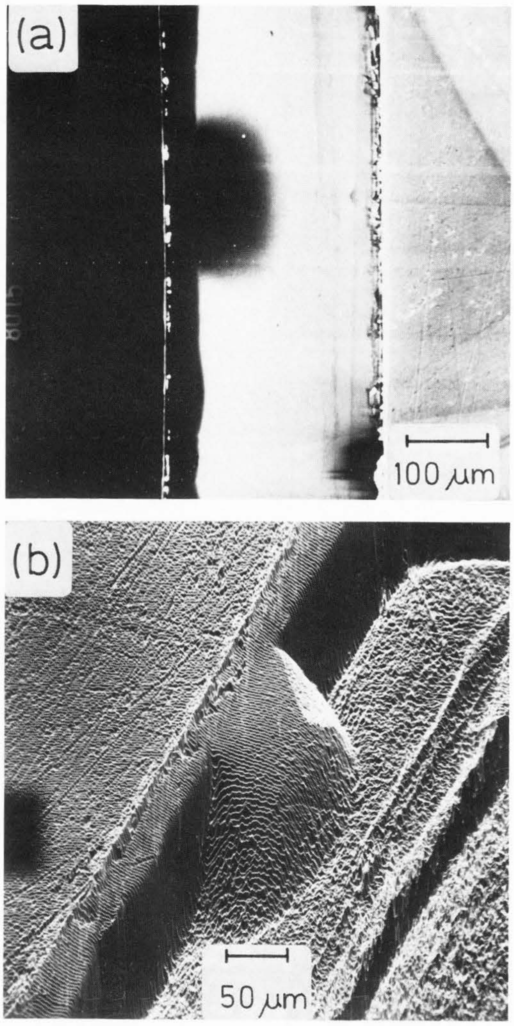

Fig. 3: Qualitative voltage contrast showing a potential inhomogeneity due to a current filament
(a) brightness modulation
(b) line scans

Fig. 3(a) shows the potential distribution when a brightness modulation of the SEM screen is used, whereas in Fig. 3(b) y-modulated line scans are used for a more detailed picture. As can be seen, a clear spatial potential inhomogeneity is observed which appears abruptly when filamentary breakdown occurs, i.e. the occurrence of the inhomogeneity is connected with a jump in the current voltage characteristic. Moreover, it has been found that each jump can generally be identified by the formation or the disappearance of such a potential inhomogeneity. As a result of the theoretical analysis /15/, we tie this inhomogeneity showing the existence of transverse electric field components to the occurrence of a current filament. This has been verified by additional measurements, the results of which are published elsewhere /9/. As a result from Fig. 3, it is concluded that in the region of low current density there is a large voltage drop near the p contact. In the filament region the voltage drop is extended into the i region. The bending of the equipotential lines is that of an electric field lens, Fig. 3(a). Fig. 4 shows the results of the potential measurements of a second diode. Again the photograph of Fig. 4(a) has been taken beyond the first jump in the current voltage characteristic of this diode showing a pronounced spatial structure in form of a potential inhomogeneity. Although the voltage contrast method used here yields only qualitative results, there is a basic agreement with a quantitative measurement using a potential probe technique as given in Fig. 4(b). In this case the potential is measured directly by pressing a tungsten probe against the semiconductor surface and by using a high impedance electrometer. Apart from contact areas, Fig. 4(b) shows that the potential structure is nearly independent of the distance from the metallic contacts pointing to a real material property.

When the current through the diode is increased, the changes in the potential distribution at first are very small. But if we pass a second jump in the current voltage characteristic a second filament is abruptly formed, see Fig. 4(c). Moreover, each clear jump in the current voltage characteristic is connected with the generation or disappearance of an additional filament of equal structure. The diameter of each filament is about 280µm which can be estimated from Fig. 4.

EBIV techniques have also been employed to examine the sample of Fig. 4. Fig. 5 shows line scans of the EBIV signals at an operating point just beyond the first jump in the current voltage characteristic. The current filament is now identified by a very complex behaviour of the EBIV signal. In the low current density regions only a small signal near the p contact is observed. A much higher signal is detected in the filament walls where very large peaks with opposite signals occur, near the p contact. Until now, no description of this behaviour can be given, but it can be foreseen that those results will ultimately lead to a better understanding of current filaments.

It is well known that Au compensated silicon pin diodes exhibit typical instabilities in the form of oscillations of the external voltage or current /6,18/. These oscillations can be observed at different values of the current voltage characteristic where several modes can be distinguished. Fig. 6 shows preliminary results in the voltage contrast mode when these oscillations, which appear at an operating point on a filamentary branch of the corresponding current voltage characteristic, are synchronized with the scanning period. The synchronisation is achieved by choosing a integral ratio of the oscillation frequency of about 30kHz to the adjustable scanning frequency. This two-dimensional observation implies that the overall instability of the sample is probably a result

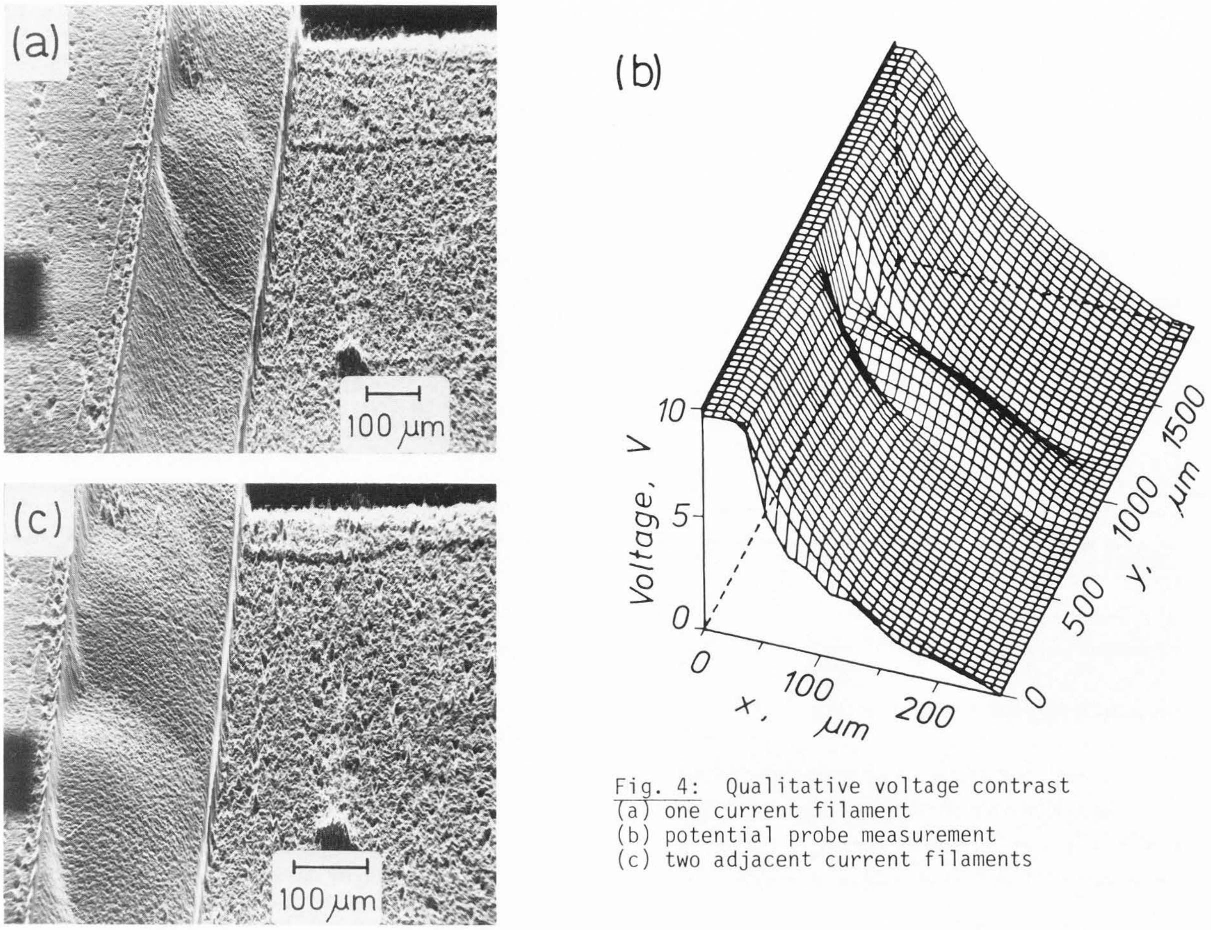

Fig. 4: Qualitative voltage contrast
(a) one current filament
(b) potential probe measurement
(c) two adjacent current filaments

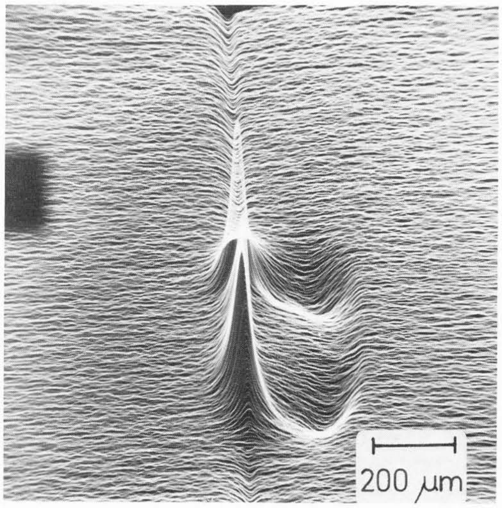

Fig. 5: Y-modulated line scans of the EBIV signal

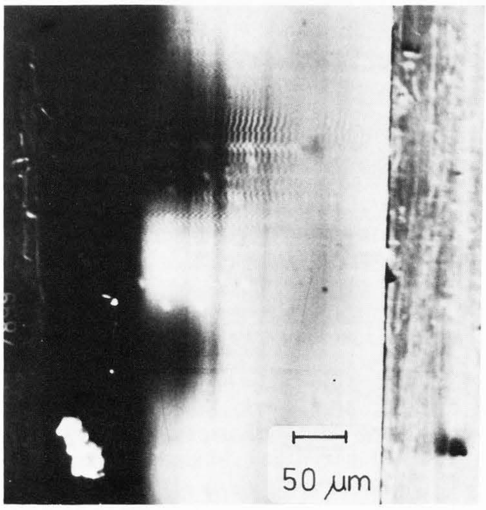

Fig. 6: Spatial potential oscillations represented by the voltage contrast (see text)

of a spatial instability in connection with the potential inhomogeneity, i. e. the oscillations can be traced back to unstable filaments.

Discussion

In summary, it has been found that by using the voltage contrast and the EBIV methods in the SEM the electrical inhomogeneities in a semiconductor diode due to current filaments can clearly be observed. Although the measurement of the potential gives only qualitative information some interesting results have already been deduced. Each jump in the integral current voltage characteristic is accompanied by the generation or the loss of a new well-defined current filament leading to a multistability of the external current. The width of each filament is constant and found to be about 280 µm in accordance with previous investigations /4/ establishing the solitary character of the structure similar to the Gunn domains. This is in contrast to the hypothesis that the filament width changes with the external current above threshold, see for example /1, 2/. Additionally, the filaments are clearly stable which seems to be contrary to the theoretical analysis /16/. A further preliminary inspection of the size of the filament along the direction of current flow reveals that with the exception of the areas close to the contacts the structure is independent of the distance from the metals establishing further on the solitary character of the filament as a result of the material properties only /15/. In this sense our measurements elucidate the close analogy between the domains and the filaments in a semiconductor material /14, 17/.

It is well known today that bistability and multistability can also yield instabilities provided that the control parameters are set to special values. As a result periodic oscillations can occur as well as chaotic motions. Our measurements have shown that Au compensated silicon pin diodes can exhibit voltage oscillations which are probably connected with unstable filaments. Hence our measurements have pointed out a close relationship between instabilities and the breakup of spatial structures. This mechanism seems also to be responsible for the behaviour of other semiconductor diodes /7, 12/.

It is therefore concluded that the SEM represents a most practical method to detect electrical inhomogeneities in semiconductor diodes. In the present case some basic physical results have been obtained concerning the formation of dissipative structures. On the other hand this method can also be applied to technical diodes where the onset of filaments is sometimes an unwanted phenomenon, for example in pn diodes, thyristors or transistors.

Finally, it should be noted that further investigations have to be carried out in order to get a better understanding of our diodes. On one hand a detailed theoretical model has to be developed including the basic physical mechanisms. On the other hand, additional experiments have already been set about to measure the temperature distribution by a layer of liquid crystals, the carrier densities by optical absorption methods, and the current density distribution by the observation of the magnetic field.

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Discussion with Reviewers

E. Schöll: In Ref. 16 it was shown theoretically that the filament walls are particularly sensitive to fluctuations of the carrier densities (cf. Fig. 4b therein), i.e. perturbations of the carrier densities in the walls grow, while perturbations in the interior or exterior of the filaments are damped out. Could this be used as an explanation of the electron beam induced voltage signal in Fig. 5 which shows distinct peaks in the walls? The opposite sign of the peaks in the high-field region near the p-contact, and in the low-field region near the n-contact, may be due to opposite transverse fields $E = -\partial V/\partial y$ and hence opposite transverse carrier gradients, as indicated in Fig. 4b.

Authors: Obviously, the EBIV signal shows a distinct sensitivity in the filament walls when charge carriers are locally generated by the electron beam. However, in the present case it is too early to give a detailed explanation or interpretation of the results on the basis of the underlying physical mechanisms in the Au compensated silicon pin diodes. This is especially true regarding the different signs of the signal.

E. Schöll: Could the observations of oscillatory instabilities (Fig. 6) be tied to periodically or chaotically "breathing" current filaments, which have recently been predicted theoretically /E. Schöll, Physica 134 B, 271 (1985)/ as a result of coupling between a longitudinal oscillatory and a transverse filamentary instability in SNDC semiconductors?

Authors: The experiments show that the externally observable oscillations can be traced back to local instabilities of the filaments. The results point to a periodically breathing or even switching of the structure. Wave phenomena seem to occur.

E. Schöll: Would it be possible to investigate the influence of the lateral boundaries upon the filaments in future work? This might shed light upon the possible dependence of the filament diameter as well as of their stability upon these boundary conditions; these questions have recently been addressed theoretically /E. Schöll, Z. Phys. B 62, 245 (1986)/. Note that in Ref. 16 the solitary current filaments have only been shown to be unstable in infinite systems under constant current conditions.

Authors: Experimentally the lateral boundaries are established by the edges of the metallic contacts, i.e. by open ends, see Fig. 1. Other types of lateral boundaries are imaginable, for example by using additional contacts, a reduced width of the metallic layers or optically generated charge carriers in order to study the influence upon the structure. Up to now we have found a clear stability of a single and also of several filaments in our devices independent of the lateral dimensions. Further work is in progress.

Reviewer I: Did you make an attempt to obtain information from EBIC with y-modulation?

Authors: As a result of the S-shaped characteristics of our devices we used impressed current conditions in order to limit the current when breakdown occurs. In that case only EBIV measurements can be applied.

Reviewer I: I have observed a multistability effect in high reverse leakage MOS and bipolar transistor junctions similar to what you have shown in Fig. 1 (current-voltage characteristic), can you comment on this effect?

Authors: In case of a steplike breakdown we believe that similar effects occur, i.e. that the breakdown is accompanied by the generation of filaments. In other words, the current flow becomes suddenly inhomogeneous when certain threshold values are attained. The physical mechanisms may be traced back to avalanche processes in pn junctions or general reverse biased depletion layers. Similar effects have recently been observed in MOS gate-turn-off (GTO) thyristors at Siemens Research Laboratories in Munich /M. Stoisiek, P. Türkes, priv. communication/.

K.D. Herrmann: Can you briefly comment on the reason for the improvement of the voltage contrast linearity?

Authors: We have achieved a more linear relation between the signal of the SE-detector and the local potential by using an offset voltage of + 10 V. Model experiments have been described and discussed in /L. Reimer (1985), Scanning Electron Microscopy, Springer Series in Optical Sciences, Vol. 45, Springer, Berlin, Heidelberg, 265-266/.

K.D. Herrmann: Do primary electron energy and current influence the generation and growth of the current filaments?

Authors: Yes, if we use a powerful electron beam (20 KeV, 10^{-8}A) the filaments can be generated as described in Ref. /13/. Until now we didn't observe a growth of a filament due to the influence of the electron beam.