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ELECTRON BEAM INDUCED CAPACITANCE

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Abstract

A model of signal formation in the Electron Beam Induced Capacitance (EBICap) mode of the Scanning Electron Microscopy (SEM) is proposed. In the frame of this model the possibilities of this technique are analyzed. It is shown that EBICap is suitable to obtain a local depletion region width and for mapping of this parameter. Experimental results demonstrating the potentialities of EBICap are presented.

KEY WORDS: Electron Beam Induced Capacitance, Scanning Deep Level Transient Spectroscopy, capacitive coupling, shallow doping, minority carriers diffusion length, Electron Beam Induced Current.

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Introduction

Development of local methods for the measurement of the doping level as well as the deep level center distribution in semiconductor crystals is very important for microelectronics. SEM methods based on capacitance measurements seem to be very promising for this purpose due to their high sensitivity. One such technique is Scanning Deep Level Transient Spectroscopy (SDLTS) which is used for studying the deep level center distribution (Petroff and Lang, 1977; Breitenstein and Heydenreich, 1985; Kononchuk and Yakimov, 1990). However there are still some problems which prevent this technique being a quantitative one. One of these problems is associated with the dependence of the SDLTS sensitivity on a local depletion region width and therefore it is necessary to use complementary methods to measure this parameter.

It is well known (Wu and Wittry, 1978; Frigeri, 1987) that one can obtain the space charge region (SCR) width W in planar Schottky diodes and even in more complex p-n structures (Kittler and Shroder, 1983) from the dependence of the collected current I in the EBIC mode on the electron beam energy E_b. But this procedure is not very suitable for mapping as it only allows one to obtain values of W and the minority carrier diffusion length L by fitting of calculated dependence of I_c on E_b to the measured one at each point and therefore needs a vast amount of time, besides, its accuracy depends on L. Another way, suggested recently (Aristov et al., 1990), is to use the EBICap mode for this purpose. Though this technique was proposed many years ago (Perov et al., 1983), up to now it is not clear what kind of an information about the local electrical properties of semiconductors can be obtained using EBICap because no model of the signal formation in this mode has been proposed. Some possible mechanisms of the EBICap signal formation are discussed and illustrated in this paper. It is shown that this technique is promising for local measurements of the depletion region width.

Instrumentation

The basic principle of the EBICap technique is based on measuring of the changes of capacitance of a planar barrier structure under an electron beam excitation. Instrumentation for this method is similar to the well known SDLTS one (see e.g. Breitenstein and Heydenreich, 1983, 1985). But while EBICap is based on measuring of the capacitance during an electron beam pulse, SDLTS consists in processing of capacitance transient signal after the end of the excitation pulse. It should be noted that both techniques allow us to use the same apparatus. A block diagram of the experimental setup for EBICap measurements is shown in Fig.1.

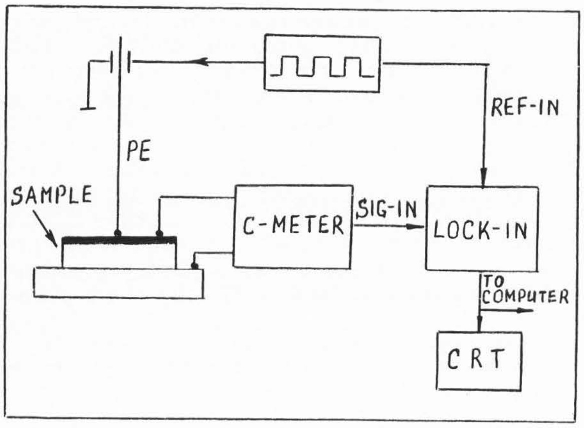

Fig.1: Block diagram of the apparatus for the EBICap measurements.

An essential part of the installation is a high sensitivity capacitance meter with parameters similar to that used for the SDLTS technique (Breitenstein, 1982). In our installation we use a capacitance bridge with low input resistance of a few ohms at the blanking frequency. Conversion of the signal into a voltage by the capacitance bridge is followed by its detection using a lock-in amplifier, the signal from the beam blanking unit of the SEM being supplied to the reference input. Finally the EBICap signal can be stored in the computer and displayed on the SEM CRT.

Model of the Signal Formation

Let us consider the possible mechanisms of EBICap signal formation . The most interesting and informative one is associated with the capacitance change caused by changes of the local space charge density due to the flow of excess minority carriers from the region of e-h pair generation, that leads to the local change of the SCR width. If the SCR width W is less than the size of the electron-hole pair generation region and diffusion length L, the number of minority carriers in the SCR region is greater than that of majority ones, which leads to an increase of a barrier capacitance in comparison with its dark value. Let us evaluate the EBICap signal in the case of an electron beam incident normally to a planar Schottky barrier on an n-type semiconductor. For the sake of simplicity we assume a homogeneous generation in an excited region. The normalized change of a capacitance of the barrier with area S is

$$\frac{\Delta C}{C} = \frac{\sqrt{N + \Delta p - \Delta n} - \sqrt{N}}{\sqrt{N_0}} \, \frac{\Delta S}{S} \qquad (1)$$

where N, N_0 are the local and average net concentrations of shallow dopants, respectively (the latter value can be obtained from C-V measurements), ∇p and ∇n are the average concentrations of minority and majority excess carriers in the SCR, respectively, ∇S is the excited area. When $W < L$, the value of $\Delta n \sim \frac{W}{W+L} \Delta p$ can be neglected in comparison with Δp. For a rough estimation, the expression for the electron induced current I_c as the product of Δp and the average hole velocity V' can be used. The latter parameter depends on the electric field and hence upon the doping level as $\sqrt{N}$ in the case of low electric fields and is independent of N when the hole velocity reaches its saturation value. Thus we obtain

$$\frac{\Delta C}{C} = \left[\sqrt{1 + \frac{I_c}{\Delta S e V' N}} - 1 \right] \frac{\Delta S}{S} \sqrt{\frac{N}{N_0}} \qquad (2)$$

In the case of weak excitation $\frac{\Delta p}{N} \ll 1$

$$\frac{\Delta C}{C} = \frac{I_c}{2eV'S} \, \frac{1}{\sqrt{NN_0}} \qquad (3)$$

From the equation (3) it is easy to see that the EBICap image can differ from the corresponding EBIC image. We can rewrite this equation as the product of the collected current and some function which spatially depends on the value of N. Therefore dividing the EBIC value by the EBICap one, it is possible to obtain the local value of the depletion region width. This rough approximation shows qualitatively the influence of different parameters on the EBICap signal.

The possibility of realization of such mechanism can be illustrated by Fig.2 which shows the images of a shallow n^+-p junction in $Hg_{0.6}Cd_{0.4}Te$ in the EBICap (a) and EBIC (b) modes. This n^+-p junction has

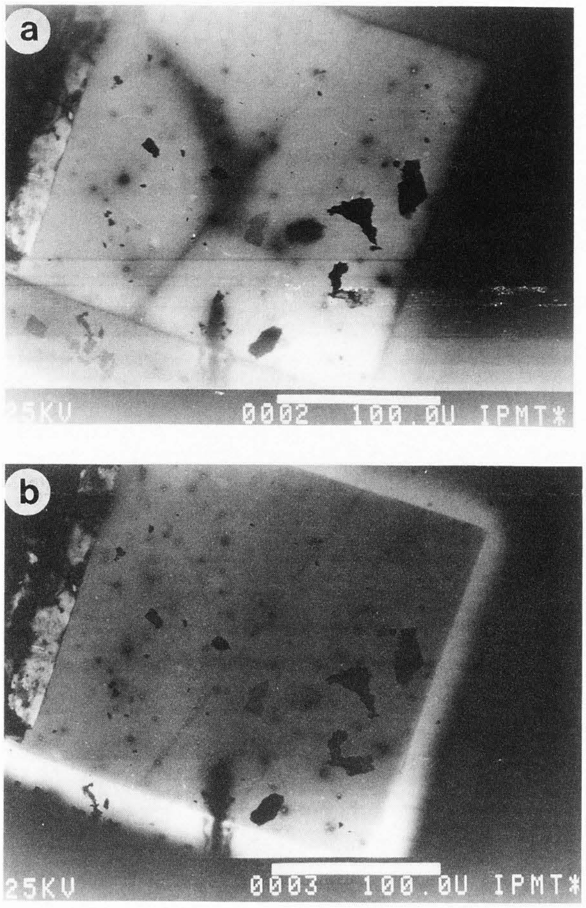

Fig.2: Images of a shallow n^+-p junction in the EBICap (a) upper and in the conventional EBIC mode (b) bottom.

been produced by an implantation of B into a p-type single crystal with free carrier concentration of $10^{15}cm^{-3}$ followed by conventional post implantation annealing. Reverse bias of 1V has been applied to the junction during measurement.

One can see a decrease of the EBICap signal in the vicinity of a grain boundary that is not revealed in the EBIC mode. This decrease can be ascribed to a decrease of W in this region according to (3). The negative signal at the outer surrounding of the n^+-region where the junction comes perpendicular to the surface in comparison with the EBIC bright strip can also be explained in the frame of our model. Indeed the numbers of excess electrons and holes are the same but in the case when the largest part of the generation region is inside the SCR the center of gravity of the minority carrier distribution is shifted to the junction plane as compared to that of majority ones. The influence of the majority carriers on the capacitance of the junction in this case can be greater than that of minority ones because according to the Poisson's equation for the flat capacitor the capacitance change is proportional to the value $\int \Delta n(z) z dz$, where z is the distance from the junction plane (Lang, 1979). Thus the sign of the capacitance change under an electron beam excitation can be changed and at an appropriate position of the beam, the dark contrast can appear. It should be mentioned that a similar effect of the contrast sign change may be obtained on deep planar p-n junctions by changing the accelerating voltage. In our case we did not see such phenomenon that points to the very low hole lifetime in the n^+-region.

Application range and limitations

Above example shows only qualitative agreement with the theory proposed, but in some cases this approximation allows to measure W with a good enough accuracy to map this parameter.

It should be noted, that it is rather difficult to satisfy the conditions when the capacitance signal is caused by the mechanism described above. First of all, as the magnitude of the EBICap signal is near the limit of the installation sensitivity ($\frac{\Delta C}{C} \sim \frac{\Delta p}{N} \frac{\Delta S}{S} \sim 10^{-5}$) it is necessary to use appropriate structures with a small barrier area (about 100x100 squared micrometers). The second limitation is associated with the total capacitance change caused by the voltage drop appearing across the structure due to the nonzero resistance of the external circuit. This voltage is proportional to the product of I_c and the external series resistance. Therefore when the input resistance of the capacitance meter or the ohmic contact resistance is large enough, the EBICap image is equivalent to the EBIC one. So it is possible to obtain the EBIC image of the structure by increasing the series resistance in the sample circuit without using a current preamplifier. Thus to get a meaningful information about W we should use samples with a low resistance and with sufficiently good ohmic contacts in order to ensure the signal in "true" EBICap mode being higher than that determined by the voltage drop across the series resistance. These limitations are very similar to those for SDLTS (Kononchuk and Yakimov, 1990), (Breitenstein and Heydenreich, 1985). Therefore the technique discussed is very promising when used in combination with SDLTS.

The effect of recharging of deep level centers by the electron beam also can cause the EBICap signal formation. But the

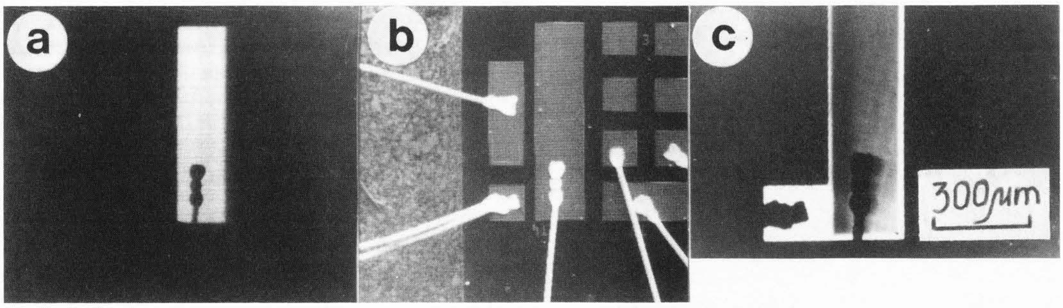

Fig.3: Images of a vertical n-p-n transistor in the EBICap (a), in the SE (b) and the EBIC (c) modes measured when the base-collector junction is connected.

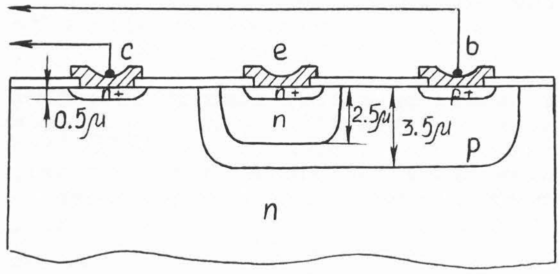

Fig.4: Cross section of transistor shown in Fig. 3.

amplitude of the signal provided by this mechanism would be comparable with that determined by the mechanism discussed above only when deep level center concentration N_t is about of Δp or higher.

One more interesting feature of this technique is its ability to visualize built-in barriers in complex structures. The images of a conventional vertical n-p-n transistor in the EBICap (a) and EBIC (c) modes are shown in Fig.3. A schematic of this structure one can find in Fig.4.

In the EBIC mode the base-collector junction connected to the preamplifier is visible while in the EBICap mode only the floating base-emitter junction is revealed. The change of potential of the disconnected barrier under an electron beam excitation causes changes in the potential of the collected junction due to capacitive coupling between these junctions. Note, that in the capacitance mode we can detect very small (about 10µV) variations of the potential of the detecting junction.

Conclusions

In this paper the possible mechanisms of the EBICap signal formation have been discussed and a semiquantitative model describing the signal has been proposed. It has been shown that using appropriate structures and experimental conditions it is possible to determine the local shallow dopant concentration. The EBICap technique also allows to analyze built-in and buried barriers in semiconductor devices. The most promising application of this technique is its using in a combination with the SDLTS because both techniques have similar structure limitations and the same equipment.

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Discussion with Reviewers

D.B.Holt: You have not quantified any of the observations you present. Could you give a value for the variation in W that is responsible for the dark contrast around the grain boundary in figure 2a, for example, either in absolute terms (μms) or as a percentage decrease?
Authors: In the case of our structure we can only evaluate the enhancement of the concentration of shallow accepters. Using the value of the maximum EBICap contrast ~10% we can give only a lower limit of the change of concentration as 15%. There are two reasons of such rough estimation. The first one is rather high excitation level used that the ratio $\Delta p/N$ was ~1, and the other is that n^+-p junction in our case is rather deep and therefore the influence of the carriers generated in n^+ region on the EBICap signal should be taken into account.

D.B.Holt: Can you give an estimate in general cases for the sensitivity of the EBICap technique?
Authors: The estimation of the sensitivity of this technique in general case is rather difficult because the signal depends on the ratio W/L in a complicated manner. But in the case when $W \ll L$ it can be done. From the equation (3) one can easily obtain $\frac{\delta N}{N} = \frac{\delta (Ic/\Delta C)}{(Ic/\Delta C)}$. If we neglect the error caused by measuring collected current we see that the sensitivity of the EBICap to the variations of W is equal to the sensitivity of ΔC signal measuring which is proportional to the excitation level and decreases with increasing of an barrier area. Using samples with area less than 100×100 μm^2 one can reach value of a few per cent.

M.Kittler: To map distribution of depletion region width the EBIC method can be used too. Thereby a comparison of EBIC signals resulting from large beam energy/low injection and low energy (R < W) /high injection is performed (see e.g. H.J. Leamy, L.C. Kimerling, S.D. Ferris, Scanning Electron Microscopy/1976 (Part VI), ed. O. Johari, p. 529-538). This technique works qualitatively, only, but has a very high sensitivity. What are the advantages of EBICap in relation to this relatively simple procedure?
Authors: Indeed the technique proposed by H.J. Leamy et al has a high sensitivity, namely $\frac{\delta N}{N} = \frac{\delta Ic}{Ic}$, but in our opinion it has some disadvantages. A contrast in the EBIC mode in the case of high injection level and W > R depends on an injection level and therefore it is possible to measure the W changes but rather difficult to obtain quantitative information about W value itself. In addition this technique can be applied only to the structures with sufficiently low doping. EBICap allows us to avoid these disadvantages, however its sensitivity becomes the same as the above technique only when using small barrier structures. Also we should limit our choice of studied objects to the structures with W<<L. Besides in some cases, e.g. when using in combination with SDLTS this technique is very simple because it needs no additional equipment.

M.Kittler: You discuss the possibility to obtain space charge region width W in planar devices from the dependence of EBIC Ic on beam energy Eb. The accuracy of W determination for this method depends on minority-carrier diffusion length L and increases with reduction of L. Does L affect W estimation by using EBICap too?
Authors: Yes, L affects W estimation using EBICap. But contrary to the above-mentioned technique the accuracy of W estimation does not depends on L when L >>W, that is in the case when the current flow is determined by the diffusion rather than excess carriers generated inside the SCR.

J.Heydenreich: You assume $\Delta p/N$ to be <<1. Indeed, taking typical values of an electric field strength of 10^4 V/cm, Ic=1μA, μ=500cm^2/Vs and S=4μm^2 a simple calculation yields $\Delta p \approx 3 \cdot 10^{13} cm^{-3}$. Hence, $\Delta p/N < 10^{-2}$ leading according to the formula given in your text for the area of your HgCdTe-sample of > $5 \cdot 10^4 \mu m^2$ a signal of $\Delta C/C < 10^{-6}$. Since the EBICap image Fig.2a shows no indication of noise, your capacitance detection limit should have been well below $\Delta C/C = 10^{-7}$. This is in contrast to your statement of $\Delta C/C \sim 10^{-5}$, therefore I doubt that the EBICap image in Fig. 2a can be interpreted according to your theory.
Authors: Indeed, we observed very low

signals and to make meaningful micrographs we had to use a large value of beam current. The value of collected current was about $3*10^{-5}$A, so the value $\Delta p/N$ was ~ 1 and $\Delta C/C \sim 10^{-4}$. Nevertheless we did not observe any presence of e-h plasma, the value of the EBIC signal was proportional to the beam current.

J.Heydenreich: From your reply I learnt that the measurement conditions have been far from being ideal: with $\Delta p/N \sim 1$ eq. (3) is no more valid, hence the EBICap signal can no more rewritten as a product of the collected current and some function of N. Moreover, with I_c as high as $3*10^{-5}$A the voltage drop across all relevant circuit resistances already generates an EBICap signal in the order of $\Delta C/C \sim 10^{-4}$ as measured. The conclusion seems to be that, having a detection limit of $\Delta C/C \sim 10^{-5}$, this technique can only be applied in the high injection regime where it works no more even semi-quantitatively but at best qualitatively.

Authors: Concerning our experimental conditions, you are right, they are near or beyond the limits of an application of eq. (3). In this case the change of capacitance due to voltage drop on the base series resistance of the diode (~10 Ohm) is comparable with that determined by eq. (3). Resulting signal is the sum of these two terms. Both of them are proportional to I_c with coefficient being constant for the first one and depending on the local N value for the second. Therefore the comparison of the EBIC and EBICap images allows to reveal local N inhomogeneities. So we can use these pictures as a qualitative illustration of the technique. Nevertheless this technique can be used for quantitative measurements even with detection limit of installation $\Delta C/C \sim 10^{-5}$ under the conditions discussed in the text of the paper.

J.Heydenreich: You totally have ignored the effect of recharging trapping centers in the space charge region due to the generated carriers. If their emission rate exceeds the lock-in frequency, their charge state may follow the chopped excitation leading to a bright or dark EBICap contrast, depending on whether minority- or majority-carrier traps are involved. Since especially for highly compensated materials the trapping center concentration may be even larger than the net doping concentration, this EBICap signal may be larger than that discussed in your paper by orders of magnitude. I argue that the difference between Fig.2a and b is mainly due to this effect.

Authors: You are quite right, that recharging of deep level centers by an electron beam can cause the change of barrier capacitance. It can be easily recognized measuring the dependence of the EBICap signal on the lock-in frequency or sample temperature. But in our experiment the difference between Fig.2a and b can not be explained by this effect, since the DLTS spectra of this structure reveal only deep level centers with net concentration both majority and minority traps less than $10^{13}cm^{-3}$.

J.Heydenreich: I agree that this effect may be recognized by measuring the temperature or frequency dependence of the EBICap signal. But since the sample cooling is limited to typically 78K, there may always be levels in the energy range below 0.1 eV that are neither detectable by DLTS nor by temperature dependent EBICap measurements. In your case, having $N \sim 10^{15}cm^{-3}$ a trap concentration N_t of $10^{13}cm^{-3}$ already could give a signal of $\Delta C/C \sim 10^{-4}$ if ΔS would exceed only 4 μm^2. But especially for high injection conditions (as in your case) the area of deep level recharging may strongly exceed the area of the main EBIC signal flow (see contribution of O. Breitenstein at DRIP-4), hence the EBICap contrast of Fig. 2a may easily be due to this effect.

Authors: It would be very difficult to agree with this comment. In our experiment we have barrier area 300x300 μm^2, and total N_t less than $10^{13}cm^{-3}$. Change of capacitance due to this effect can be evaluated as $\Delta C/C \sim (N_t/N)*(\Delta S/S)$, having $\Delta S \sim 3x3 \mu m^2$ we obtain $\Delta C/C \sim 10^{-6}$. Under high injection conditions the value of ΔS may be some greater, it is correct, but ΔS depends on collected current as $lg(I_c)$ and can not strongly exceed the area of the EBIC signal formation (see f.e. Kononchuk O., Yakimov E.(1990) J. Crystal Growth 103, 287-290.). Deep level centers with an activation energy below 0.1 eV are not recharged by an electron beam at room temperature because its thermal emission rate which is equal to $\sigma V N_v * \exp(-\Delta E/kT)$, where σ is the capture cross section, V is the thermal velocity, N_v is the density of states in the valence band, T - temperature, is some orders of magnitude greater than the capture rate which is equal to $\sigma V \Delta p$ for any values of σ and N_t.