Charge deep-level transient spectroscopy of Al/intrinsic diamond/p⁺-Si Schottky diodes

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Abstract
Charge deep-level transient spectroscopy (Q-DLTS) and the feedback charge capacitance method (FCM) were applied to Al/intrinsic diamond/p-Si diodes, using the top Al electrode as a Schottky gate. The Q-DLTS data recorded over the temperature range of 90–450 K could be split into two components: (i) a peak of the signal due to a discrete energy level, the hole emission of which is thermally activated by \( \Delta E = 0.29 \pm 0.02 \) eV; (ii) a broad spectrum of relaxation times manifesting itself as a signal that increases continuously on heating the diodes toward the ultimate temperature. To exclude any effects caused by the silicon back contact (Al), Q-DLTS spectra taken at different polarities of the filling pulse were compared. The related FCM capacitance–voltage measurements at the uppermost temperature revealed no changes in the capacitance with bias if sampling the time domain capacitance in the microsecond region. Over a longer timescale an excess capacitance was detected as expected on the basis of the complementary Q-DLTS data. Taking into account the absence of any capacitance changes at lower temperatures and/or short observation times (excitation), it is concluded that the defects reside in the polycrystalline diamond layer rather than at the diamond/silicon interface.

1. Introduction

The steadily increasing interest in electronic devices based on diamond is due to their numerous outstanding physical and chemical properties, such as mechanical hardness, thermal conductivity, radiation hardness (Mainwood 2000) and corrosion resistance. Apart from these basic features, there is the acceptable mobility of both electrons and holes at ambient temperatures in this wide bandgap material, thereby signalling its competitiveness with widely used silicon. In order to open the way towards commercially available diamond related electronic elements and circuits it is essential to understand the physics of metallic contacts attached to diamond (Aoki and Kawarada 1993, Miyata and Dreifus 1993, Tachibana et al 1993), whether ohmic or rectifying. It is well established that the formation of metal carbides leads to ohmic contacts while pure metals like Au or Al provide rectifying (Schottky-like) contacts to diamond. Keeping in mind that n-type diamond is not readily available, development of the device is centred around majority carrier devices such as Schottky diodes and field-effect transistors or devices utilizing electron injection. Since large-area single-crystal diamond wafers are not yet available, thin-film diamond-on-silicon technology is a prime candidate for prospective industrial production.

In addition to problems connected with the absence of shallow dopants and carrier freeze out at low temperatures, the issue of the role that charged defects play emerges. From what was published on this topic in the past it follows that deep-level transient spectroscopy (DLTS) introduced by Lang (1974, 1979) may already have contributed valuable information. We start our brief review of the work carried out to date by citing a few of the numerous reports by Polyakov and his group (Polyakov et al 1998, Druz et al 1998, Polyakov et al 1999) who used charge DLTS (Q-DLTS) of diamond-like thin films. One of the outcomes of their studies was the finding that the signal from the dominant defects in
such films changed significantly after exposure to water or isopropyl alcohol, thereby making the films suitable for sensor applications. Muret et al (1999, 2000) investigated boron-doped homoepitaxial diamond films by current Fourier DLTS, detecting a deep level at 1.4 eV above the valence band edge $E_V$ in samples submitted to annealing at 800 °C in ultrahigh vacuum. When applying oxygen plasma treatment to the sample before the Schottky contact (Au, Al, Er) deposition, another deep level at $E_V + 1.16$ eV above the valence band can be detected. For both defect levels the capture cross sections were estimated. According to Zeisel et al (1998) and Nebel et al (1999), who tested thin films of homoepitaxially grown boron-doped diamond by means of capacitance–voltage, DLTS and optical DLTS methods, there are two defect levels at $E_V + 0.83(0.9)$ eV and $E_V + 1.25$ eV, respectively. The density of the former amounted to $N_T \approx 10^{15}$ cm$^{-3}$, a value comparable to the density of ‘shallow’ boron dopants of $7 \times 10^{15}$ cm$^{-3}$.

Our present report is aimed at presenting the defect properties of intrinsic diamond layers on heavily boron-doped p$^+$-Si substrates. In contrast to the previous studies, the presence of a relatively shallow discrete trapping energy level along with a continuum of energy levels is observed, combining the feedback charge capacitance–voltage method (FCM) developed by Mego (1986) with a modification of the charge DLTS introduced by Kirov and Radev (1981) and Farmer et al (1982). With regard to the extremely low capture rates of the traps they are assigned to the diamond film, rather than to the Si side of the diamond/p$^+$-Si interface. Any possible interference with the back contact response can be excluded in a simple way. An estimate of the concentration of the discrete level is provided benefiting from the saturation of the signal at sufficiently high amplitudes of the filling pulse.

2. Experimental

2.1. Sample preparation

Intrinsic diamond films on heavily boron-doped Si substrates were prepared by the well known hot filament chemical vapour deposition technique (HFCVD) (Dua et al 1993). P-type (111) (diameter 100 mm, thickness 525 µm, resistivity 0.8–1.2 Ω cm) silicon wafers from Wacker–Chemitronic GmbH were used as substrates. The wafers were cleaned in HF acid to remove the surface oxide layer, sonically cleaned in diamond slurry in methanol and finally vapour degreased in isopropyl alcohol. Diamond film was grown using the HFCVD technique using a home-built facility. CH$_4$ and H$_2$ gas mixtures in the ratio (3 : 732 by volume) were fed to tungsten filaments heated to a temperature of around 2000 °C, subsequently dissociated and deposited on the substrate placed underneath. The depositions were carried out at sub-atmospheric pressure and the substrates were heated to ~800 °C. Other pertinent parameters were optimized as described in Dua et al (1993). The substrate holder was rotated very slowly to attain the desired homogeneity of the film. The thickness of the film was estimated from Fabry–Perot interference in a reflectance IR spectrum. The sample was annealed in vacuum at ~800 °C before depositing Al gate electrodes. Al dots 0.5 mm in diameter were evaporated onto the cleaned diamond surface, to obtain rectifying Schottky-like contacts. The nominally undoped diamond films are slightly p-type. The nominal thickness of the diamond film amounted to $d = 4.5$ µm. Finally, a large-area ohmic Al back contact was evaporated onto the back of the p$^+$-Si wafer. The cryostat used enabled FCM and Q-DLTS measurements within the temperature interval of 77 to 450 K.
2.2 Methods

The above-mentioned FCM represents a time-domain technique of measuring the capacitance of a diode, as a complementary tool to the widely used ac impedance instrumentation. The FCM basic unit is an integrator with a feedback capacitor \( C_f \) between the output and the inverting input (virtual ground). The top Al gate electrode of our Al/diamond/p+-Si/Al diode is virtually grounded while the back Al contact is fed by the output of a programmable bias source. The latter provides the inverted quiescent reverse gate potential \(-U_g\), as well as a train of excitation pulses \(-\Delta U\) superimposed on \(-U_g\). In other words, during the pulse there is a total gate bias of \( U_g + \Delta U \) acting on the Schottky gate contact on the top of the diamond layer, see figure 1. Normally, in the Q-DLTS mode we use the negative polarity \( \Delta U < 0 \) of the pulse to fill excess traps in a p-type semiconductor attached to the gate. It may be obvious that for the rest of the repetition period (period-pulse) there is the applied bias \( U_g \) on the gate. After a predefined number of cycles an averaged correlated charge or capacitance reading is taken, as explained later.

Each bias step \( \Delta U \) applied to the diode capacitance \( C_x \) causes a potential jump \( \Delta U_{out}(t) \) at the integrator output, due to charging the feedback capacitor \( C_f \) with \( t \) being time. Since the respective charges across \( C_x \) and \( C_f \) are equal one to another, we can write

\[
C_x = \frac{\Delta U_{out}(t)}{\Delta U} C_f. \tag{1}
\]

Evidently, the integrator may be viewed as a charge-to-voltage converter. The question may arise, where the time dependence of \( C_x = C_x(t) \) is coming from. Having a trap-free diode, there would be a time-independent potential jump \( \Delta U(0) \) at the output, due to the instantaneous capacitance of the junction \( C_x(0) = (\Delta U(0)/\Delta U) C_f = \varepsilon_s A/\varepsilon U_g \), \( \varepsilon_s \) is the permittivity of the semiconductor, \( A \) is the gate area and \( \varepsilon U_g \) is the depletion region width at the bias \( U_g \). Should there also be a discrete energy level capturing charge carriers during the timescale of the observation, then we have a time-dependent component \( Q(t) \) of the charge across \( C_x \) (and across \( C_f \) as well). Restricting our considerations to the case of a p-type semiconductor (\( \Delta U < 0 \) and \( U_g > 0 \)), during the pulse some portion of the trapping levels captures majority carriers (holes). After removing the pulse, the equilibrium is restored by emitting the previously captured charges. Assuming for simplicity that exponential kinetics apply to both the capture and emission of the charge carriers. The two processes are governed, of course, by different time constants, \( \tau_c \) and \( \tau_e \) respectively, as long as \( \Delta U \) is greater than \( kT/e \), with \( T \) being temperature and \( e \) electronic charge. Now we have an increase of the portion \( \delta Q \) of the excess captured charge during the pulse, expressed as \( \delta Q = Q(t) - Q(t_0) \), with \( Q(t) \) being the total charge corresponding to the number of traps that may have changed their occupancy for the pulse-duration pulse \( \gg \tau_c \). The removal of the pulse \( (U_g + \Delta U \rightarrow U_g \text{ transition}) \) is followed by emptying the portion of the previously refilled traps

\[
Q(t) \approx Q_0[1 - \exp(-t/\tau_c)] \exp(-t/\tau_e). \tag{2}
\]

The total charge across \( C_x \) during the rest of the period is composed of two components: there is the constant charge \( Q(0) = C_x(0) \Delta U \) proportional to \( \Delta U(0) \) in figure 1, and the transient charge \( Q(t) \) defined by equation (2). The latter corresponds to the part of the transient output voltage saturated at \( U_{tr}^\infty/\Delta U \). The interval reset coincides with the switch across \( C_F \) being closed.

Now we are ready to consider the algorithm utilized for processing the output voltage \( U_{out} \) of the charge-to-voltage converter by means of a programmable three-channel correlator. One should take three samples of the converted charge response in the following sequence:

1. Channel 1 is activated after a delay \( t_0 \) relative to the front of the pulse \( \Delta U \) so as to sample the baseline just before the arrival of the trailing edge of the pulse, \( Q(t_0) \).
2. Channels 2 and 3 are activated at delays of \( t_2 \) and \( t_3 \), respectively, programmed with respect to the trailing edge of the pulse \( \Delta U \), giving signals proportional to \( Q(t_2) \) and \( Q(t_3) \).

As the final step, the signals proportional to \( Q(t_i) \) \((i = 0, 2, 3)\) are combined according to the rule

\[
C_x = \frac{Q(t_0) - 3/2 Q(t_2) + 1/2 Q(t_3)}{\Delta U}. \tag{3}
\]

The resulting formula for the time-domain capacitance describes a few comments, keeping in mind that the processed charge corresponds to that one across \( C_F \) rather than across \( C_x \). At the end of the pulse \( C_x \) comprises the acquired excess charge \( Q(t_0) = Q_0[1 - \exp(-\Delta U/\tau_c)] \), in accordance with equation (2). Not so for \( C_F \), since due to the reset (delay \( t_0 \) approaching pulse, figure 1) the experimentally sampled term \( Q(t_0) \) is practically zero. Now the charge released from the traps in response to \( \Delta U \) over the rest of the period is charging \( C_F \)

\[
Q_F(t) = Q(t) - Q(t_0) = -Q(t_0) \left[1 - \exp(-t/\tau_c)\right]. \tag{4}
\]

According to equation (4) the introduction of the reset initiated by closing the switch across \( C_F \) is equivalent to shifting the transient charge baseline by \( Q(t_0) \). An important point to make is that the absolute position of the baseline \( Q(t_0) \) does not influence the measured capacitance, a crucial feature mediated by correlating the outputs of the three channels, see equation (3). The event of taking the first sample may be classified as baseline probing.

Apart from \( Q(t_0) \), for assessing \( C_x \) the quantity \( Q(t_2) \) should be sufficient, still the third sample taken at \( t_3 = 3t_2 \) becomes important in situations when the diode draws a considerable leakage (steady-state) current. The latter, if integrated, would cause a parasitic linear drift of the output voltage of the input integrator, resulting in either an over- or under-estimated value of the true capacitance, in dependence on the polarity of the bias \( U_g \). It is easy to show that any linear drift during the rest of the period is eliminated by including the third sample value \( Q(t_3) \). If using very short delays \( t_2 \), the resulting capacitance corresponds essentially to that of the instantaneous capacitance \( C_x(0) \) of the depletion region. In contrast, if the corresponding time constant of the traps approaches \( t_2 \), we register a capacitance in excess of \( C_x(0) \). A saturation of the excess capacitance is observed for \( t_2 \gg \tau_c \) at the value \( C_F \Delta U/\Delta U \). Note that there is normally no peak of the excess capacitance at any prominent

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bias, as long as the spatial density of the traps $N_T$ remains uniform. A more detailed description of the trap-limited excess capacitance is provided elsewhere (Thurzo and Grendel 1992). The capacitance–voltage data from this paper corresponds to the amplitude of the pulse of 0.06 V.

There is a simple transition from the FCM to the Q-DLTS, since the latter uses the same hardware (three-channel correlator). Apart from detuning the amplitude $\Delta U$, the only step needed for switching from FCM to Q-DLTS is shifting the first sampling event in channel 1 to the rest of the period, defining instead the modified delay $t_1$ versus the trailing edge of the pulse $\Delta U$. The correlated charge $\Delta Q$ at the output of the correlator in Q-DLTS mode corresponds with a weighted sum

$$\Delta Q = Q^*(t_1) - 3/2Q^*(t_2) + 1/2Q^*(t_3),$$

$$t_2 = 2t_1, \quad t_3 = 4t_1,$$

In the Q-DLTS mode applied to a p-type semiconductor the pulse with an adjustable $\Delta U < 0$ acts as a filling pulse initiating the capture of holes, so equation (2) also remains valid for Q-DLTS, except for the amount of the total released charge $Q_0^*$ which is equal to $Q_0$ only when using the same $\Delta U$ for both the FCM and Q-DLTS, respectively.

On introducing a dimensionless variable $x = t_1/\tau_c$, the response $\Sigma(x)$ of the filter represented by equation (5) peaks at $x_m \approx 1$. As to the amount of the charge $\Delta Q_m$ detected at $x_m$, there is a significant difference compared to the FCM mode at saturation, namely only the fraction $\Delta Q_m \approx 0.17Q_0^*$ of the total released charge $Q_0^*(\text{pulse} \gg \tau_c)$ is detected at the temperature of the signal maximum $T_m$. This drawback of the filter defined by equation (5) is counterbalanced by both an improved energy resolution, compared to that of the filter originally introduced by Lang (1974), and by the constant term plus the linear drift-rejection capability of our filter. As a consequence, the charge $C_1(0)\Delta U$ is completely filtered out, a prerequisite for achieving high trap-detection sensitivity. It is noteworthy that we have neglected the factor which expresses the spatial sensitivity of Q-DLTS (Thurzo et al 2000). Nevertheless, after performing a set of thermal scans at different rate windows $e_p(T_m) = (t_1)^{-1}$, the thermal activation energy $\Delta E$ of the emission rate $e_p$ is estimated in the usual way (Lang 1974, 1979).

3. Results and discussion

The results that follow cover both FCM and Q-DLTS measurements in the temperature region from 90 to 460 K, that are not covered by previous studies. From a series of FCM experiments we selected the capacitance–voltage characteristics of a diamond-based Schottky diode, registered at the highest temperature of the interval covered. At ambient temperature and below there was only a slight temperature dependence of the diode capacitance that remained independent of bias even for pulse = 31.5 ms and period = 63 ms. The two $C-U_g$ plots shown in figure 2 are a nice example of an excess trap-limited capacitance. The curve at the bottom corresponds evidently to the instantaneous (geometrical) capacitance $C_1(0)$ of the device that did not change with the applied gate bias $U_g$. The small step in $C$ observed at $U_g = 0$ V stems from a hardware-specific artefact.

Both the pulse and $t_2$ were too short for the available traps to respond to $|\Delta U| = 0.06$ V. The situation changed when using longer pulse durations and/or delays $t_2$, and one example is reproduced at the top of the figure. Besides the observed significant increase of the capacitance at positive gate biases, there is even an additional incremental rise of the capacitance when biasing the diode in the forward direction ($U_g < 0$). This is consistent with the almost symmetric current–voltage curve showing a very small rectification ratio of about 1.5. From this picture we can predict a sufficient sensitivity for the detection by Q-DLTS, mainly by biasing the gate of the diode to more negative values during the filling pulse. As evident from figure 3 there is a measurable Q-DLTS spectrum evolving with the bias pulse amplitude $\Delta U$ as predicted. The saturation of the whole spectrum at $U_g + \Delta U \approx -6$ V coincides remarkably with what was expected when considering the FCM data. Apart from this predicted behaviour, there are two typical features in the spectra:

(i) a well resolved discrete Q-DLTS peak at 192–196 K;
(ii) a continuously increasing signal, becoming dominant at about the ambient temperature, which, however, does not exhibit a maximum in the temperature range investigated.

The position of the former on the temperature axis for the given $t_1$ is almost fixed, and the slight shift of the peak
toward elevated temperatures on increasing the amplitude of the pulse might be connected with dragging of the peak by the background signal. It is, therefore, easy to assess the thermal energy $\Delta E$ from the individual maxima of the set of Q-DLTS records depicted in figure 4 with the plots corresponding to different rate windows. There is a horizontal (dashed) line on the right side of the figure, the crossovers of which with individual $\Delta Q - T$ plots will be treated later in this section. The resulting Arrhenius’ plot is presented in figure 5, along with the demanded quantity $\Delta E = (0.29 \pm 0.02)$ eV. This value is significantly lower than the well established position of the shallow boron acceptor at $E_V + 0.37$ eV in diamond (Zeisel et al 1998). Another reason for distinguishing between the 0.29 eV level and that of 0.37 eV is the significantly lower concentration of the former, as will be documented further.

A question may arise concerning the spatial location of the 0.29 eV defect level. At first sight the presence of a discrete trapping level in the $p^+$ Si substrate or even at the diamond/$p^+$ Si interface cannot be excluded. To shed more light on this issue, additional experiments were conducted. This proved to be crucial in exploring the capture kinetics of the defect in question. The duration pulse of the filling pulse was varied while keeping its amplitude $\Delta U$ constant, see figure 6. Let us consider first the discrete peak at $T_m \approx 215$ K and the emission time constant $\tau_e(T_m) = t_1 = t_2/2 = 1.5$ ms. Using large-signal excitation ($\Delta U \gg kT/e$), the capture time constant $\tau_c$ of a discrete energy level is in general much shorter than $\tau_e$. In fact there is no saturation of the overall Q-DLTS response at 215 K and pulse $= 5$ ms; after subtracting the background the amplitude of the discrete peak remains practically the same even for longer pulse durations. With respect to this we conclude that the duration pulse of 5 ms was sufficient for saturating the 215 K peak amplitude. Unlike the 215 K peak, the saturation of the tail demanded a duration pulse as long as 50 ms. This holds practically for the temperature range below the peak temperature down to 90 K. This discrepancy in the filling kinetics of the two processes is even more accentuated with reference to figure 3, showing the simultaneous saturation of both the discussed signals with the pulse amplitude. Figure 3 is suggestive of an identical spatial localization of the defect groups. With regard to the unusually slow capture of the charge carriers by the traps responsible for the tail of the background signal we suggest identifying the traps with defects on the diamond side of the diode. The diamond layer is composed of microcrystallites and thus it is likely that the charge transport over long distances is limited by grain boundaries acting as potential barriers of varying heights, rather than by bulk conductivity of the crystalline phase. Such a view is partially supported by the observation of the broad spectrum of the emission relaxation times represented by the tail. It is mandatory to provide at least semi-quantitative evidence for dealing with such a case.

For simplicity we begin with the assumption of a uniform (bulk) density of defect states $N_T(x, \Delta E) = \text{const}$ (box-like distribution), $x$ now standing for the distance from the top Al/diamond interface. Before writing down an adequate formula for the Q-DLTS response, we appeal to the equation (11) from a previous work (Thurzo et al 2000) which expresses the amount of the external charge released from a discrete trap. The charge $Q_i^*$ is identified here with the quantity $Q_0^*$ introduced above

$$Q_i^* = -A c N_T(x, \Delta E) \Delta x_c (1 - x_c/w), \quad (6)$$

where $x_c$ denotes the depth of the centroid of the excited volume element of width $\Delta x_c$. To avoid integration of the
correlated charge $\Delta Q(\Delta E_i)$ (see equation (5) of this paper) over a continuum of thermal energies $\Delta E_i$, we perform a summation of the individual contributions from a discrete spectrum of energies confined in the interval $(\Delta E_{\text{min}}, \Delta E_{\text{max}})$

$$\Delta Q^* = \sum_{\Delta E_{\text{min}}}^{\Delta E_{\text{max}}} \Delta Q(\Delta E_i). \quad (7)$$

An illustrative example of what equation (7) yields for the box-like distribution is plotted in figure 7. The demarcation energies of the distribution are shown as the relatively small peaks at $T_{\text{mi}} = 145 \text{ K}$ and $T_{\text{m2}} = 275 \text{ K}$, respectively, computed according to equation (5) that applies to the $\Delta Q^*$ versus $T$ plot of a discrete energy level. Without providing an exact analysis, we point out that the full width at half maximum (FWHM) of a $\Delta Q(T)$ peak due to a discrete energy level $\Delta E_i$ is a linear function of temperature. Then, if performing the summation according to equation (7), there is the almost linearly rising Q-DLTS response confined between the two temperatures $T_{\text{mi}}$ and $T_{\text{m2}}$ corresponding to demarcation energies 0.2 and 0.4 eV, respectively, see figure 7. The $\Delta Q^*$–$T$ plot does not reflect the shape of the distribution function $N_T(x, \Delta E_i)$, as expected for the sum of the discrete peaks of varying FWHMs (amplitudes). It is recommended to take rather the derived (reduced) $\Delta Q^*/T$ versus $T$ plot, after which step a qualitative picture of the shape of $N_T(x, \Delta E_i)$ versus $\Delta E_i$ emerges, with $T$ as a measure of $\Delta E_i$. An important point to make is that we took a discrete value of the capture cross section for the simulation.

Another question to be answered is how to deduce the demarcation energies $\Delta E_{\text{min}}$ and $\Delta E_{\text{max}}$, respectively, from a set of experimental data. It seems to be mandatory to record a series of Q-DLTS spectra belonging to different rate windows. The simulation presented in figure 8 shows that for intermediate energies within the interval considered the plots tend to merge with each other, a finding which is to some extent consistent with our experimental data—figure 4. In contrast, at the temperature regions close to the demarcation energies the individual signals are fairly separated. In what follows we suggest a procedure that should enable us to find the demarcation energies. Figure 9 contains the reduced $\Delta Q^*/T$ plots and may serve as a guide in explaining the procedure. We suggest drawing a line through both the rising and descending portions of the plot with the line crossing the inflexion points on either side. In this way we obtain two sets of temperatures $T_{\text{mi}}$ needed for the related Arrhenius’ plots. For the lower demarcation energy of 0.2 V we found a fairly closely matching value of $\Delta E_{\text{min}} \approx 0.199 \text{ eV}$, while the resulting upper limit $\Delta E_{\text{max}}$ amounted to 0.397 eV. It is also possible to apply the procedure to the ‘flat’ portion of the reduced Q-DLTS response (dashed curve), arriving at an intermediate $\Delta E \approx 0.274 \text{ eV}$. Turning back to the experiment (figure 4), nonexponential behaviour of the Q-DLTS spectra is evident at first sight if we concentrate on the horizontal dashed curve crossing the set of the experimental $\Delta Q^*$–$T$ plots, and assess the distances between neighbouring $T_m$ values. Yet, at shorter observation times ($t_1 < 6 \text{ ms}$) the Arrhenius’ plot could be fitted fairly well by a straight line, giving an intermediate value of $\Delta E \approx 0.46 \text{ eV}$ of the broad spectrum expected to extend above 450 K. The tendency towards saturation at longer sampling times implies we are approaching unrealistic thermal energies.

One of the standard outcomes of the DLTS method should be an estimate of the density of traps $N_T(x, \Delta E)$. Since the
trap-free (instantaneous) capacitance did not change with bias this task is far from feasible. Put in other words, there is no chance of reconstructing the real spatial and energy profile of the traps from the methods used. To do this, we use the process of saturating the signal when driving the diodes to negative biases by the pulse \( \Delta U \). If we assign the saturation to a complete filling followed by a total depleting of the traps in the diamond layer, we can provide an estimate of the average density \( N_T \) of the discrete 0.29 eV level

\[
N_T = \frac{\Delta Q (T_m)}{\Sigma_m e \Delta d}.
\]

Taking \( \Delta Q (T_m) = 5 \times 10^{-14} \text{C}, \Sigma_m = 0.17, A = 1.96 \times 10^{-7} \text{m}^2, d = 4.5 \mu\text{m} \), we arrive at \( N_T \approx 2 \times 10^{18} \text{m}^{-3} \). With reference to figures 3 and 7, respectively, the maximum trap density corresponding to the tail at 450 K might be of the same order of magnitude. Analysis of the reduced signals \( \Delta Q^*/T \) point to a distribution function \( N_T(x, \Delta E_i) \propto \exp(\Delta E_i/E_0) \) with \( E_0 \) being a constant for the selected rate window. Extending the temperature region of the measurements should ensure more reliable data for finding a representative value of \( E_0 \).

The last issue to be treated is the possible role the back Al contact plays if excited by the bias step. It is widely accepted that for large-signal excitation the amount of the correlated charge detected on emission is much greater compared to its capture-limited counterpart, the latter occurring at a lower temperature, if observable at all. There is valuable information contained in figure 10, which shows that the discrete peak and the tail were initiated by driving the top Al/diamond interface to accumulation by \( \Delta U < 0 \). On the other hand, the poorly discernible Q-DLTS peak at \( T_m \approx 275 \text{K} \) is assigned to the back contact because of its ability to emit holes in response to \( \Delta U > 0 \). The position of the peak on the temperature scale is very close to the melting point of ice and so it is likely that there were some residual ice crystals contributing to charges in response to the pulsed bias.

### 4. Conclusions

We have provided some evidence for a discrete energy level characterized by a thermal energy of \((0.29 \pm 0.02) \text{eV}\), detected along with a tail of the signal that is expected to reflect the polycrystalline morphology of the diamond films. Both contributions to the Q-DLTS signal showed simultaneous saturation upon biasing the diodes in the forward direction during the excitation pulse. There is probably no change in the space charge in the heavily doped silicon below the relatively thick high-resistivity diamond layer in response to the pulsed bias even at 450 K, as shown by the constant value of the instantaneous time-domain capacitance, irrespective of the bias. Residual water adsorbed at the back contact of the p+-Si substrate could be resolved as a Q-DLTS peak of quite a small amplitude. As to the methodology of profiling distributions in heterostructures comprising undoped (intrinsic) semiconductors, new concepts and ideas are needed.

### References


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