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Dissociative electron attachment and dipolar dissociation of H^- electron stimulated desorption from hydrogenated diamond films

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In this work we report, a study of the mechanism of H^- electron stimulated desorption (ESD) from hydrogenated diamond films for incident electron energies in the 2–45 eV range. Two types of experiments were carried out in order to assess the nature of the ESD processes leading to desorption as a function of incident electron energy: (i) kinetic energy distribution (KED) of H^- and (ii) H^- anions yield at fixed ion energy (FIE) measurements. The KED measurements show that for incident electrons of up to ~11 eV the most probable kinetic energy of H^- ions monotonically increases from about 1.7 to 3.3 eV. For higher incident electron energies, the ion energy distribution peaks at about 1.5 eV and is nearly constant. From these measurements it is derived that the H^- ESD cross section has a resonance behavior displaying two well-defined peaks at 9 and 22 eV and a monotonic increase with a threshold at ~14 eV as a function of incident electron energy. From the KED and FIE spectra the 9- and 22-eV peaks are interpreted as due to dissociative electron attachment via a single Feshbach anion resonance state, albeit accessed directly and indirectly, respectively. A possible intermediate process involving a well-known electronic excitation of the hydrogenated diamond at 13 eV is suggested. For incident electron energies higher than ~14 eV, H^- ESD proceeds also via dipolar dissociation processes.

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INTRODUCTION

Whereas negative ion electron stimulated desorption (ESD) by low-energy electrons have been studied extensively in condensed gases at low temperatures[1–12] only very few studies have concerned chemisorbed systems.[13] In this paper we report, on the mechanisms of negative ions H^- ESD from hydrogenated diamond films for incident electron energies in the 2–45 eV range. To the best of our knowledge only one work has been reported on the study of H^- ESD from a chemisorbed system in this energy range.[13] In that study, the H^- ESD cross section from hydrogenated silicon surfaces [Si(111):H-1×1] was found to display a peak at ~6 eV, which was attributed to dissociative electron attachment (DEA).

In an analogy with gas phase molecules ion production by electron impact in the 0–30 eV range ESD from adsorbates results essentially from two processes: namely, molecular fragmentation into a stable anion and a neutral species, which occurs via dissociative electron attachment (DEA), and fragmentation into an ion pair, that is, dipolar dissociation (DD).[1] DEA of adsorbed species is similar to the gas phase: an electron impinging on the solid surface is temporarily captured in an excited, localized chemisorbed state to form a transient negative ion state near the surface. If the negative ion state is relatively long lived with respect to electron re-emission (i.e., $>10^{-14}$ s) and dissociative within the Franck-Condon region of the neutral chemisorbed ground state, dissociation into a stable anion and ground—or excited neutral surface state may occur. DEA from surfaces involves typically a core-excited state (two electrons, one hole) where the excess electron is bound to the excited site. Generally, DEA processes display a resonance dependence on incident electron energy, and in most cases, these occur at energies from a few eV up to ~15 eV. ESD may proceed also from DD, which involves dissociation of an electronically excited state into an ion pair. In most cases, DD processes monotonically increase from a threshold with incident electron energy. Maxima or resonancelike structure above the threshold for DD have been reported and in all cases assigned to complex mechanisms involving multiple electron scattering or loss processes within the bulk prior to resonance electron attachment.[3,8,10,14] Unlike the interaction of slow electrons with gas phase molecules, the presence of the surface introduces many-body dynamical effects that are not well understood.[10,15–19]

The interaction of energetic electrons and photons with hydrogenated diamond surfaces has been studied by us and others.[20–24] It has been determined that irradiation of photons and/or electrons with such surfaces results in emission of hydrogen ions and neutrals. In the case of H^+ ESD the main mechanism is through a core hole relaxation,[20,21] whereas H^- ESD has been determined mostly to be induced by low-energy electron irradiation.[21,22] However, the mechanism of H^- ESD induced by low-energy electron bombardment has not been determined and it is the subject of this research work. ESD of H^+ of hydrogenated single crystal diamond surfaces using an incident electron energy of 1000 eV combined with time of flight techniques have shown that the kinetic energy distribution (KED) of H^+ ions displays two components, a slow and a fast one, depending on the annealing temperature.[20] In agreement, we found that photon stimulated desorption (PSD) of H^+ for photon energies above the C(1 s) threshold, the KED shows peaks at 1.7 and 4 eV.[20] These studies suggest that ESD and PSD of hydrogen ions combined with KED measurements may be a powerful tool for the determination of the bonding configuration of hydrogen on the diamond surface and subsurface.

In addition to the fundamental aspect, the understanding of ESD processes on carbon surfaces has broader implications, some of them are mentioned here. Considering that the interstellar medium contains a large amount of nanodiamond particles and hydrogen, understanding the effect of low-energy electrons irradiation (either coming from outside or within the solid as secondary electrons) on the surface chemistry of hydrogenated diamond is very interesting for the assessment of physico-chemical phenomena of outer space. Hydrogenated diamond displays negative electron affinity (NEA) and it is therefore very attractive for the detection and emission of electrons. In this case, depletion of adsorbed hydrogen results in degradation of its NEA and should be understood. From a broader technological perspective, understanding ESD of hydrogenated semiconductor surfaces is of large importance for the development and optimization of electron-beam lithography and dry etching processes.

EXPERIMENT

Diamond films were deposited onto *p*-type doped silicon substrate using a methane/hydrogen gas mixture by the microwave chemical vapor deposition (MW-CVD) method. The thickness of the films was $\sim 10\ \mu m$ with a characteristic microcrystalline size of 2–3 μm. After deposition, the diamond films were further exposed to a MW hydrogen plasma at the same substrate temperature, gas flow, and power as those used for the growth process. The surface composition and phase purity of the films were examined *ex situ* by various electron spectroscopies. The Auger and electron energy loss (EEL) spectra of the sample showed the characteristic C(KLL) line shape of diamond, and surface and bulk plasmon of diamond at 23 and 33 eV, respectively. X-ray photoelectron spectroscopy showed that the film surface was free of impurities (other than hydrogen). Photodesorption experiments carried out using photon energies in the 280–320 eV range [C(1 s) region] showed that only H^+ and H^- desorbes from the surface.[20] These results show that the diamond film was hydrogenated and free of other impurities. This hydrogenation procedure is expected to result in a homogeneously hydrogen termination of the diamond microcrystallites surfaces that compose the film, as well as the incorporation of hydrogen in the subsurface region. It might be possible that also some surface chemical heterogeneity occurs due to hydrogen adsorption on grain boundaries.

The apparatus for studying ESD was described in detail earlier.[12] Briefly, it consists of a hemispherical electron monochromator as electron gun, a hemispherical energy analyzer in line with a quadrupole mass filter for kinetic energy analysis, and identification of desorbed ions and electrons. The components are housed in an ultrahigh vacuum chamber (base pressure in the 10^{-11} mbar region) with a two layer μ-metal shielding to block the earth's magnetic field. The primary electron energy is calibrated with respect to vacuum level by measuring the difference between the elastic peak and the true secondary zero energy electrons in the presence of the diamond film thus correcting for changes of the work function. The range of incident electron energies, E_i could be varied in the 5–50 eV range. The incident electron current was measured with a Faraday cup as function of E_i and found to be in the 7–9 nAmp range. The electron beam diameter is 0.3 mm. All relevant spectroscopic data were normalized by the incident electron current. The energy resolution of the electron beam at the target is estimated as 80 meV (FWHM). The electron beam was oriented at 60° from the surface normal. The anion energy analyzer and quadrupole can rotate from zero to 90° from the surface normal. In our ESD experiments, the analyzer was positioned at 0°. The zero of the kinetic energy scale for the desorbing anions was taken as the secondary electrons emission cutoff with an accuracy of 100 meV. The incident electron energy at the surface was corrected to take into account charging effects as determined by this cutoff. The energy resolution of the analyzer for both ions and electrons is estimated to be 100 meV. Charging effects were minimized by illuminating the diamond surface by a UV lamp (near UV).

Two types of ESD measurements were performed:

(1) The kinetic energy distribution (KED) of anion or electrons were measured for different incident electron energies, E_i.

(2) The yield of ions desorbing with a defined kinetic energy (fixed ion energy yield mode—FIE mode) as a function of E_i.

In addition, electron emission spectrum were measured in the same manner as described for the anions.

Prior to the ESD experiments the system was backed to 150 °C and the sample was subsequently annealed to 600 °C to induce desorption of any residual adsorption of water vapor. All ESD experiments were performed at room temperature.

The possibility that the ESD experiments result in a substantial depletion of chemisorbed hydrogen or electron-beam induced surface damage that may affect our results were examined by measuring the H^- KED for $E_i = 9$ eV in between experiments. By these alternating measurements, the reproducibility of our results could also be verified. Also, to avoid large exposures of a particular area to the electron beam, experiments were carried on different areas of the sample surface. Typical electron flux exposures of a particular area were altogether of the order of 10^{17} electrons$*$cm^{-2} over a time of several hours. Finally, all reported results were reproduced on several (five) MW plasma hydrogenated different diamond films samples. By these procedures, the reproducibility of our ESD results and chemical state of the surface were comprehensively corroborated.

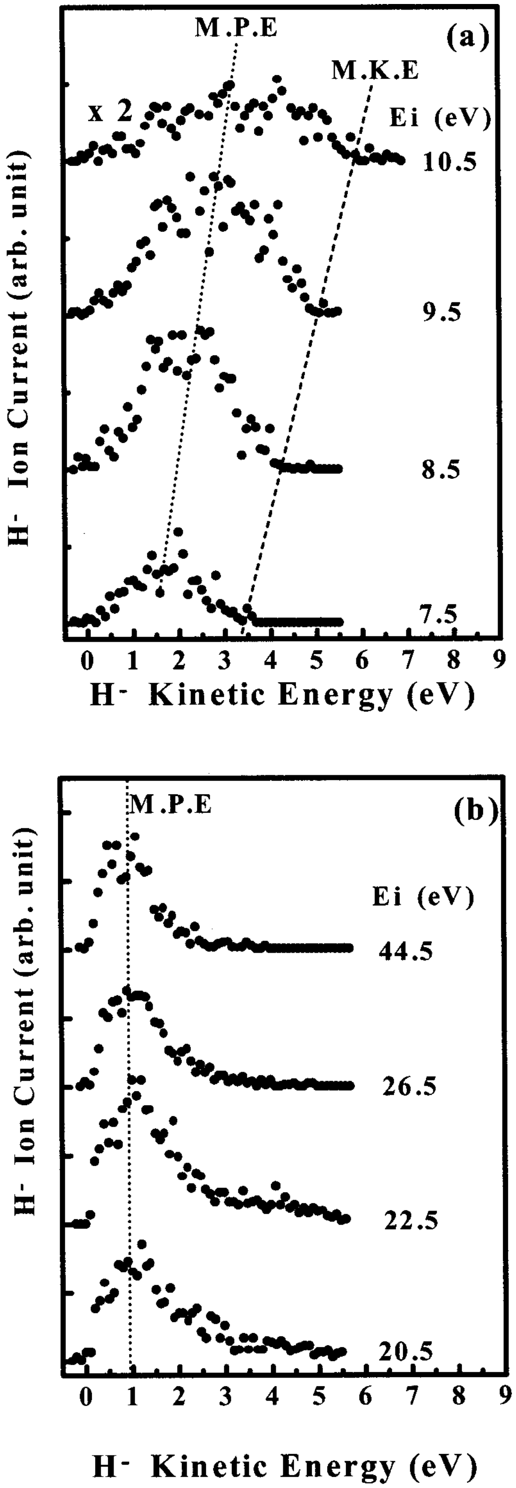

FIG. 1. (a) and (b) kinetic energy distributions (KED) of H^- for different E_i.

RESULTS

A. KED of H^- as a function of incident electron energy

The KED of the ions was measured for incident electron energies in the 7–45 eV range. For E_i smaller than 6 eV, no H^- ions could be measured. The KED of the ions measured for different E_i values are shown in Figs. 1(a) and 1(b). Each KED curve can be characterized by its onset, full width at half maximum (FWHM), most probable energy (MPE) and maximum kinetic energy (MKE). In Fig. 2 the integral intensity of the H^- ions as calculated from the KED curves is displayed as functions of E_i.

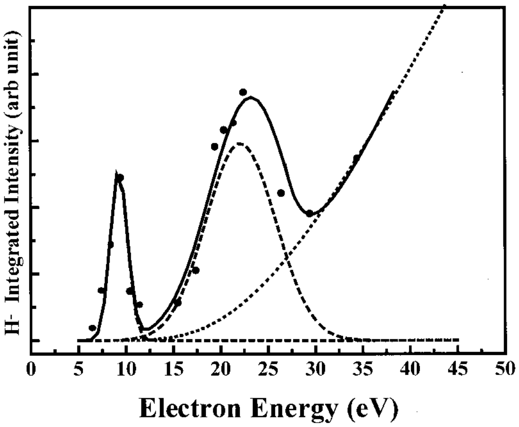

FIG. 2. Integral intensity of the H^- as function of E_i.

From Fig. 1, the KED of the ions may be divided into two regimes as function of E_i: (i) E_i smaller than ~12 eV [Fig. 1(a)] and (ii) E_i larger than ~12 eV [Fig. 1(b)]. Below we elaborate on the characteristic features of the KED in these two regimes:

(i) For E_i smaller than ~12 eV, the KED's are dominated by broad curves, which are shown in Fig. 1(a) for E_i values in the 7.5–10.5 eV range. For these E_i values, the FWHM increases from 1.6 to 4 eV, while the MPE increases from 1.7 to 3.3 eV. The onset of the KED was measured at nearly ~0 eV and was found to be independent of E_i. Concurrently, the MKE for each KED curve shown in Fig. 1(a) increases from a value of about 3.4 to 6.1 eV. The dependence of MKE as a function of E_i was calculated from the KED curves shown in Fig. 1(a), resulting in a linear curve with a slope of 0.9 ± 0.1.

(ii) For higher E_i (above ~14 eV) the KED is dominated by a peak (MPE) at ~1 eV with an onset at nearly 0 eV kinetic energy. The MPE onset, and FWHM of the KED in this energy range are nearly independent of E_i. In addition, it is very important to notice that a low-intensity contribution at higher ion energies can be seen in the KED that reaches a maximum value for $E_i \sim 22$ eV. The existence of this high energy, but low intensity, component of the KED curve is supported by the FIE results described below.

The curve shown in Fig. 2 is proportional to the total cross section for ESD of H^- as a function of E_i for the particular geometry of our experiment. This figure displays two well-defined peaks centered at 9 eV and at ~22 eV and a monotonic increase above ~14 eV. The FWHM of the first peak is 2.6 eV, whereas that of the second is difficult to determine unambiguously as this peak is superimposed onto a monotonic increasing curve, however, we estimated it to be ~8–10 eV. As seen from this figure the peak height of the 22 eV peak is about twice that of the low-energy peak at 9 eV. The dependence of the cross section on E_i clearly suggest that H^- ESD involves three processes: two of a resonant

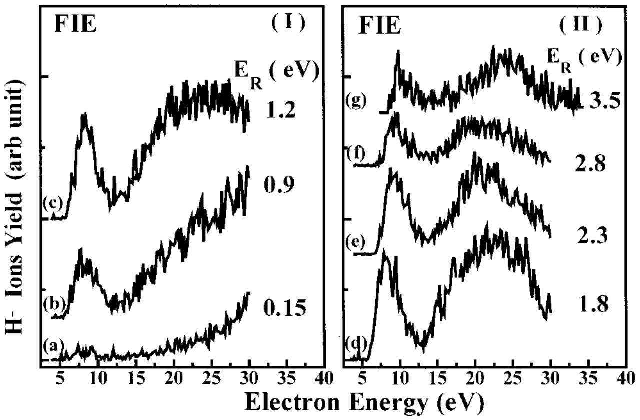

FIG. 3. (I) and (II) FIE for different ion energies as function of E_i.

nature centered at 9 and 22 eV and a third with a threshold at ~14 eV that increases with E_i. To guide the eye, the curve shown in Fig. 2 has been decomposed into two Gaussians centered at 9 and 22 eV and a monotonic increase function with an onset at ~14 eV.

B. FIE as a function of E_i

The ion yield was measured at different specific fixed ion energies (FIE) as a function of E_i. In Fig. 3 curves (*a*)–(*g*) FIE spectra are shown for H^- kinetic energies of 0.15, 0.9, 1.2, 1.8, 2.3, 2.8, and 3.5 eV, respectively, in the 4–30 eV E_i range.

As seen from Fig. 3 curves (*a*), the FIE spectrum measured at 0.15 eV ion energy shows a small peak at 8 eV followed by monotonic increase with an onset at 14 eV. At an ion energy of 0.9 eV, the 8 eV peak's intensity increases [Fig. 3 curves (*b*)] and a shoulder at ~22 eV starts to became evident in the spectrum. As the ion energy is increased (1.2 eV and above) the low-energy peak maximum increases from 8 to 9 eV and a quite symmetric peak centered at 22 eV appears. Concurrently, the high-energy component in the FIE spectrum (above the second peak at 22 eV) decreases in intensity, reaching a nearly background value for ion energies of 2.8 eV and above.

The FWHM of the 8–10 and 22 eV peaks, as measured for ion energies higher than 1.8 eV, are 2.3 and 8–10 eV, respectively. These values are similar to the FWHM of the peaks shown in Fig. 2. It is important to notice that the height ratio of the 8–9 and 22 eV peaks is nearly constant and similar for ion energies larger than ~1.8 eV. The intensity of both peaks goes through a maximum and then decrease as a function of fixed ion energy (as the FWHM of these two peaks was found to be constant with ion energy, it is justified to compare the peaks intensity by their height). This means that both peaks describe phenomena having the same dependence on ion energy, albeit induced by quite different incident electron energies.

DISCUSSION

As seen from Fig. 2, the dependence of the cross section on E_i clearly suggests that H^- ESD involves at least three processes: two of a resonant nature centered at 9 and 22 eV and a third with a threshold at ~14 eV that increases with E_i. To guide the eye, we performed a rough deconvolution of the cross section into three separate components: two Gaussians centered at 9 and 22 eV and a monotonically increasing function with a threshold at ~14 eV.

The peak at 9 eV in the H^- ESD cross section, which is below the onset for DD, is attributed to a DEA. Similar observations have been made in the case H^- ESD from condensed saturated and unsaturated hydrocarbons molecules measured in the 0–20 eV range.[25–27] From all those works it becomes evident that low-energy ESD of systems containing CH bonds are characterized by a resonance at ~10 eV associated with DEA followed by a monotonic increase with a threshold at ~16–18 eV. It was also found that the peak position of the DEA process was similar for saturated hydrocarbons with different chain lengths, the onset for the DD process was found to decrease from ~18 to ~16 eV with increasing chain length.

The similarity of H^- ESD from condensed hydrocarbons and hydrogenated diamond surfaces may be rationalized, so that the C-H(*ads*) surface bonding configuration resembles to a large extent the C-H bonding in methane. This is reflected in the vibrational spectrum of hydrogenated diamond surfaces by high-resolution electron-energy-loss spectroscopy.[28,29] In addition to chemisorbed hydrogen, the diamond films may also contain some subsurface hydrogen whose bonding configuration is not well understood.[30,31]

From the KED curves shown in Fig. 1, the thermodynamic limit of the H^- ESD desorption induced by DEA may be considered. In an analogy of the gas phase, for a particular value of E_i the maximum kinetic energy $E_{k,\max}$ of the desorbing ion can be approximated by:[1]

$$E_{k,\max}=(1-b)[(E_i+E_p)-D+A]-E_p, \qquad (1)$$

where E_p is the induced-polarization energy of the medium, and b is the mass ratio of H over that of an effective CH mass that should take into account the coupling of the receding C atom to the solid as the H^- ion desorbs. D is the dissociation energy of the C-H(*ads*) bond and A is the electron affinity of H^-. Considering the mass difference between C and H and the influence of the solid on the recoil of the surface C atom, b is expected to be a small number: $b \ll 1$, therefore a linear relationship between E_i and $E_{k,\max}$ with a slope of nearly one is expected. The value of $E_{k,\max}$ may be determined from the KED curves shown in Fig. 1(a) in which only the DEA process is active and is equal to MKE. From the KED curves, a linear relationship was obtained between MKE and E_i with a slope of $0.9+/-0.1$, as expected. Then the value of b calculated from the experimental fit is $0.1+/-0.1$. This is, within experimental errors, similar to the maximum expected value in the case of a free CH bond of $\frac{1}{13}$. The agreement between the kinematics of the dissociation process and the similarity in the cross section strongly suggests that the DEA process may indeed by very well described by a localized picture resembling that of the gas phase.

Furthermore, extrapolation of $E_{k,\max}$ to zero in Eq. (1) renders a D-A value of 3.7 eV. Taking $A=0.75\,\mathrm{eV}$ renders a D value of 4.35 eV in remarkable agreement with the experimental value for the C-H(ads) bond energy [Ref. 32 and references therein]. The agreement between the values derived using Eq. (1) for b and D and the experimental ones, really suggests that H^- DEA from hydrogenated diamond follows in its thermodynamic limit the behavior of the simplest possible C-H gas phase species. However, very rich dynamical processes take place as reflected in the KED curves.

For E_i above ~14 eV, two processes became evident in the H^- ESD cross section (Fig. 2): one which is resonant and obtains a maximum at ~22 eV and a second one associated with DD as inferred from its monotonic increase with E_i from an onset of ~14 eV. As seen from Fig. 3 curves (a), the FIE spectrum measured at 0.15 eV ion energy shows a small peak at 8 eV followed by monotonic increase with an onset at 14 eV. This monotonic dependence is a manifestation of the DD process that occurs with a threshold at this onset. For ion energies of 1.2 eV, the contribution of the 22 eV peak and DD processes to H^- desorption overlaps. For ion energies larger than 1.8 eV, the contribution of the DD to the desorption process is less prominent as apparent by a reduced contribution of the monotonic increase. Therefore, for fixed ion energies larger than ~2 eV, the contribution of the DD process may be neglected. Consequently, it may be concluded that the DD process gives ions whose contribution is at low kinetic energies energy in the KED curves seen in Fig. 1(b) as a peak centered at ~1 eV. But this does not exclude ions in this low-energy range coming from the second resonance.

Maxima or resonancelike structures appearing in the ESD anion yield from condensed systems above the DD threshold have been reported previously.[3,8,10,14] The 22 eV peak may be the results of three different processes: (i) attachment of an electron to a high-energy core hole state (Feshbach-type resonance): such states have been observed, i.e., in DEA of H^- from water ice;[3] (ii) resonant DD in this case, a Feshbach resonance relaxes into a lower energy DD state;[14] (iii) multiple electron scattering or loss events prior to electron attachment leading to DEA.[8,10]

To assess which of these processes is the dominant one, the KED and the FIE spectra shown in Figs. 1(a), 1(b), and 3, respectively, are considered. It is expected that desorption processes originating from the same resonance state accessed through different intermediate states should display the same KED of the H^- ions as E_i is varied. As seen from Fig. 3 curves (d)–(g) the FIE spectrum displays two well-defined peaks at E_i values of eight (which shifts to 9 eV as the fixed ion energy is increased) and 22 eV. Moreover, at the ion energy values at which the FIE spectra are measured (from 1.8 to 3.5 eV) the relative intensity of these two peaks is constant. Both peaks go through a maximum in intensity as functions of fixed ion energy and then decrease. The physical meaning of maintaining a constant relative intensity is that the KED of the H^- ions is similar, and consequently, the desorption process display the same dynamics. The similarity in the desorption dynamics, thus, indicates that these two peaks consist of H^- ions that originate from an identical resonance state.

A resonance DD process being responsible for the 22 eV peak is disputed. The constant intensity ration between the two peaks at ~9 and ~22 eV measured in the FIE spectrum means that the KED of ion desorbing from these two resonances is very similar. This is a very unlikely situation for two ions desorbing from two different excited states.

The possibility that the 22 eV peak is associated with a high-energy Feshbach resonance is also objected on the following grounds. Considering that the 9 and 22 eV resonances result in very similar KED would mean that the separation between states has to be exactly the same in the Franck-Condon region and at infinite internuclear distance again, a very unlikely situation. In fact, an initial excitation into a higher energy excited Feshbach resonance is expected to result also in a different KED. The fact that it is not the case, suggests that both peaks reflect desorption processes involving the same core-hole resonance state as discussed above.

Considering that the 8–9 eV peak was associated with a Feshbach resonance, then based on the above analysis, the 22 eV resonance is associated with electron attachment into the same resonance, albeit through an intermediate process where the incoming electron loses part of its energy to a well-defined excitation of the solid. In addition, secondary electrons of appropriate kinetic energy produced through multiple electron scattering may be involved in H^- ESD through DEA. Such processes are defined here as an indirectly dissociative electron attachment (IDEA). To further support this assignment, one should determine the intermediate process that would result in an energy loss to an incident 22 eV electron leaving it with 9 eV, the energy required to excite the negatively charged core hole resonance. Alternatively, as true secondary electrons may also be involved in the excitation process, one has in this case, to show that for an incident electron energy of 22 eV, secondary electrons of appropriate energy are produced. Furthermore, one should account by the different FWHM of the 8–9 and 22 eV peaks, as measured in the FIE plots shown in Fig. 3 of ~2.6 and ~8–10 eV, respectively.

The IDEA process may involve a loss event as the intermediate excitation, and/or be excited by secondary electrons. Enhancement of secondary electron emission at a particular energy may be a result of a primary loss event and, therefore, these two channels for the production of electrons of appropriate energies may actually be connected. Electron energy loss spectroscopy (EELS) measurements of diamond surfaces by low-energy electrons showed the existence of a 13 eV loss peak assigned to an interband transition between the valence band and a high-energy conduction band state.[33,34] The FWHM of this peak, as determined from the deconvoluted EELS spectra measured for an incident electron energy of 100 eV is ~7 eV. Thus, incident electrons of 22 eV that underwent a loss process of 13 eV have an energy of 10 eV, remarkably similar to the energy required to resonantly excite the core hole resonance. The FWHM of the second resonance then is expected to be determined by the convoluted

FWHM of the 13 eV loss with that of the direct DEA that are ~7 and ~2 eV, respectively. The expected convoluted value is 7.3 eV. This value is similar to the measured value of 8–10 eV. These results suggest that the 8–9 eV anion resonance may be accessed through an intermediate loss of the primary electron, in support of this mechanism.

A detailed analysis of the intermediate processes leading to the IDEA at 22 eV should, in principle, render the relative intensity of the 9 and 22 eV peaks as measured in the FIE spectra. However, this analysis is beyond the scope of this work. Such an analysis should consider not just the energy distribution of the scattered electrons involved in electron attachment, but also their quantum state. Whereas the symmetry of the incident electrons exciting the first resonance at 9 eV is a plane wave as they propagate from the vacuum into the solid, the symmetry of the secondary and inelastically scattered electrons is expected to be different. Such differences in the quantum state of the electrons is expected to result in variations in the cross section for electron attachment.

Next we compare the total H^- yield with the FIE spectra measured as a function of E_i displayed in Figs. 2 and 3. The peak height of the 22 eV peak is about twice that of the low-energy peak in the cross-section spectrum (Fig. 2) whereas the height of these two peaks in the FIE spectrum, for ion energies larger than 1.8 eV, is similar [Fig. 3 curves (*e*)–(*g*)]. This difference is due to the fact that in the total cross section (Fig. 2) the contribution of IDEA and DD overlaps, whereas in the FIE spectrum, the contribution of these processes are separated by preselecting the appropriate ion energies.

Remarkably, the cross section for H^- ESD from hydrogenated diamond films and hydrocarbon films[25–27] show very similar features (in the electron energy range that a comparison can be carried out). These results suggest that H^- ESD processes in both cases follow a similar mechanism, suggesting that DEA is mainly determined by the nature of the local chemical bond that is similar, to some extent, in the case of saturated hydrocarbons and fully saturated hydrogen surfaces. Solid state effects in the ESD mechanism are reflected by the presence of the second peak centered at ~22 eV. In this case, according to our interpretation, an intermediate process, possibly involving multielectron scattering processes—a solid state effect—is involved in the ESD process.

The effect of the solid on the ESD processes is expected to be prominent in the dynamics of desorption, i.e., during the time interval the H^- ions are moving away from the surface at which most complex many-body phenomena occur.[8,10,15–17,19] The interaction between the receding H^- ion and the solid results in energy losses that are reflected, eventually, in the shape of the KED of the desorbing ions and shown in Fig. 1. It is expected that the desorption dynamics will be affected by surface temperature, isotopic effects, and the exact position of the adsorbed species with respect to the surface. Dynamical aspects of H^- ESD processes from hydrogenated diamond surfaces are most interesting and will be considered in a separate work.

After discussing the different mechanisms via which H^- ESD may occur, a question of large interest is whether or not the results presented in this work may be useful for the determination of the bonding configuration of hydrogen on diamond surfaces, can it help to determine the presence of surface versus subsurface hydrogen or adsorption on grain boundaries? These are long-standing open questions and most important to understand the electronic properties of hydrogenated diamond surfaces. It is possible that a study of the desorption dynamics as reflected in the KED curves, combined with controlled *in situ* hydrogenation of the diamond surfaces, may be the answer. At the present time, we are engaged in such a study and promising results are obtained.

In summary, we have shown that low-energy electron stimulated desorption of H^- from hydrogenated diamond surfaces display a resonance behavior as a function of incident electron energies: the H^- ESD cross section displays two well-defined peaks at 9 and 22 eV. The 9 eV peak is associated with an excitation of a Feshbach resonance that leads to H^- dissociative electron attachment. It was determined that also the second peak at 22 eV is associated with the same resonant excitation of the C-H chemisorbed bond, albeit accessed indirectly. For incident electron energies higher than ~14 eV, H^- proceeds also via DD. Characteristic KED of H^- associated with DD and DEA processes were determined.

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[1] L. Sanche, Scanning Microsc. **9**, 619 (1995).

[2] M. A. Huels, L. Parenteau, and L. Sanche, Phys. Rev. B **52**, 11 343 (1995).

[3] W. C. Simpson, M. T. Sieger, T. M. Orlando, L. Parenteau, K. Nagesha, and L. Sanche, J. Chem. Phys. **107**, 8668 (1997).

[4] K. B. K. Tang, R. Azria, Y. Le Coat, M. Tronc, and R. E. Palmer, Z. Phys. D: At., Mol. Clusters **38**, 41 (1996).

[5] P. Rowntree, L. Parenteau, and L. Sanche, J. Chem. Phys. **94**, 8570 (1991).

[6] L. Siller, M. N. Hedhili, Y. Le Coat, R. Azria, and M. Tronc, J. Chem. Phys. **110**, 10 554 (1999).

[7] M. Lachgar, Y. Le Coat, R. Azria, M. Tronc, and E. Illenberger, Chem. Phys. Lett. **305**, 408 (1999).

[8] R. Azria, L. Parenteau, and L. Sanche, J. Chem. Phys. **87**, 2292 (1987).

[9] Q.-B. Lu, Z. Ma, and Theodore E. Madey, Phys. Rev. B **58**,

16 446 (1998).

[10] H. Sambe, D. E. Ramaker, L. Parenteau, and L. Sanche, Phys. Rev. Lett. **59**, 505 (1987).

[11] M. Tronc, R. Azria, Y. Le Coat, P. Cloutier, and L. Sanche, Chem. Phys. **254**, 69 (2000).

[12] M. Tronc, R. Azria, Y. Le Coat, and E. Illenberger, J. Phys. Chem. **100**, 14 745 (1996).

[13] M. Berheim and T.-D. Wu, *DIET V*, Surface Science Vol. 31 (Springer-Verlag, New York, 1993).

[14] D. Antic, L. Parenteau, and L. Sanche, J. Phys. C **104**, 4711 (2000).

[15] M. Michaud, P. Cloutier, and L. Sanche, Phys. Rev. B **48**, 11 336 (1993).

[16] M. Michaud, P. Cloutier, and L. Sanche, Phys. Rev. B **47**, 4131 (1993).

[17] M. Michaud, P. Cloutier, and L. Sanche, Phys. Rev. B **44**, 10 485 (1991).

[18] R. Azria, Y. Le Coat, M. Lachgar, M. Tronc, L. Parenteau, and L. Sanche, Surf. Sci. **436**, L671 (1999).

[19] D. L. Mills, Phys. Rev. B **45**, 36 (1992).

[20] A. V. Hamza, G. D. Kubiak, and R. H. Stulen, Surf. Sci. **237**, 35 (1990).

[21] A. Hoffman, M. Petravic, G. Comtet, A. Heurtel, L. Hellner, and G. Dujardin, Phys. Rev. B **59**, 3203 (1999).

[22] C. Goeden and G. Dollinger, Appl. Surf. Sci. **147**, 107 (1999).

[23] H. J. Hopman, J. Verhoeven, and P. K. Bachmann, *Diamond 99* (unpublished).

[24] A. Hoffman, M. Petravic, G. Comtet, A. Heurtel, L. Hellner, and G. Dujardin, Appl. Phys. Lett. **73**, 1152 (1998).

[25] P. Rowntree, L. Parenteau, and L. Sanche, J. Phys. C **95**, 523 (1991).

[26] P. Rowntree, L. Parenteau, and L. Sanche, J. Phys. Chem. **95**, 4902 (1991).

[27] P. Rowntree, L. Sanche, L. Parenteau, M. Meinke, F. Weik, and E. Illenberger, J. Chem. Phys. **101**, 4248 (1994).

[28] T. Aizawa, T. Ando, M. Kamo, and Y. Sato, Phys. Rev. B **48**, 18 348 (1993).

[29] H. Kawarada, in *The Physics of Diamonds*, Proceedings of the International School of Physics ''Enrico Fermi,'' Course CXXXV The Physics of Diamonds, p. 505–531, 1997 (IOS Press, Amsterdam, Oxford, Tokyo, Washington D.C.).

[30] H. J. Looi, L. Y. S. Pang, A. B. Molloy, F. Jones, M. D. Whitfield, J. S. Foord, and R. B. Jackman, Carbon **37**, 801 (1999).

[31] H. J. Looi, M. D. Whitfield, J. S. Foord, and R. B. Jackman, Thin Solid Films **343**, 623 (1999).

[32] K. Bobrov, B. Faisgeer, H. Shechter, M. Folman and A. Hoffman, Diamond Relat. Mater. **6**, 736 (1997).

[33] A. Hoffman, P. Paterson and S. Prawer, Nucl. Instrum. Methods Phys. Res. B **52**, 63 (1990).

[34] A. Hoffman, K. Bobrov, B. Fisgeer, H. Shechter, and M. Folman, Diamond Relat. Mater. **5**, 76 (1996).