

## Role of the Dopant in the Superconductivity of Diamond

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We present an *ab initio* study of the recently discovered superconductivity of boron doped diamond within the framework of a phonon-mediated pairing mechanism. The role of the dopant, in substitutional position, is unconventional in that half of the coupling parameter  $\lambda$  originates in strongly localized defect-related vibrational modes, yielding a very peaked Eliashberg  $\alpha^2F(\omega)$  function. The electron-phonon coupling potential is found to be extremely large, and  $T_C$  is limited by the low value of the density of states at the Fermi level. The effect of boron isotope substitution is explored.

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In a recent paper [1], the superconductivity of boron-doped (B-doped) diamond was evidenced experimentally with a transition temperature  $T_C$  of 4 K. This work follows the discovery of superconductivity in doped silicon clathrates [2,3] ( $T_C = 8$  K), a cagelike silicon material which crystallizes in the same  $sp^3$  environment as the diamond phase. Further, the superconductivity of carbon-based clathrates was predicted on the basis of *ab initio* simulations [3,4].

Even though the reported temperatures are low, the superconducting transition of column IV semiconductors is of great interest as it concerns very common materials. Further, in the case of the carbon clathrates, it has been predicted that the electron-phonon (*e-ph*) potential  $V_{ep} = \lambda/N(E_F)$  [ $N(E_F)$  the density of states at the Fermi level] may be extremely large [3,4]. Finally, the superconductivity of hole-doped strongly bonded covalent systems is reminiscent of that of the  $MgB_2$  compound [5].

As compared to the cagelike clathrate phase, diamond is difficult to dope as the network is much denser. This explains why the superconductivity of doped diamond was never observed, as only quite recently a doping in the limit of a few percent could be achieved. It is for a boron concentration  $c > 10^{22} \text{ cm}^{-3}$  that a degenerate semiconductor or metallic character can be obtained [1].

Recently [6,7], a first theoretical study of the superconductivity of B-doped diamond within an elegant virtual-crystal approximation was proposed. In this approach, the crystal is made of “averaged carbon-bore atoms” [nuclear charge  $Z = (1-x)Z_C + xZ_B$ ] within the standard 2 atoms/cell structure of diamond, and B atoms are not considered explicitly. As such, the superconductivity of B-doped diamond was analyzed in terms of Bloch-like delocalized electron and phonon “average” states.

In this work, we study by means of *ab initio* calculations the electron-phonon coupling in B-doped diamond. We consider explicitly a large supercell with one B atom in substitution. The metallic character of the doped system is evidenced and the deviations from a simple rigid

band model are discussed. We show further that the B atoms yield very localized vibrational modes which contribute to half of the *e-ph* coupling parameter  $\lambda$ , in large contrast with the picture conveyed by the virtual-crystal approximation. The value of  $\lambda$  is calculated *ab initio*, yielding an unusually large *e-ph* coupling potential  $V_{ep}$  or deformation potential  $D$ .

Our calculations are performed within the local density approximation (LDA) to density functional theory (DFT) [8] and a pseudopotential [9] plane-wave approach. A 55 Ryd energy cutoff and a  $(4 \times 4 \times 4)$  Monkhorst-Pack [10] sampling of the Brillouin zone (BZ) showed good convergence for structural relaxations. The phonon modes and the *e-ph* coupling matrix elements were obtained within the framework of perturbative DFT [11]. Because of the computational cost, phonons were calculated at the  $\mathbf{q} = \Gamma$  point only. This is equivalent to a  $(3 \times 3 \times 3)$  sampling of the undoped diamond BZ.

For the calculation of the average *e-ph* matrix elements over the Fermi surface, required to evaluate  $\lambda$ :

$$\lambda = N(E_f)V_{ep} = 2N(E_f)\sum_{\mathbf{q}\nu}\langle|g_{q\nu}|^2\rangle/\hbar\omega_{q\nu}, \quad (1)$$

$$\langle|g_{q\nu}|^2\rangle = \int_{\Omega_{\text{BZ}}} \frac{d^3k}{\Omega_{\text{BZ}}} \sum_{n,n'} |g_{q\nu}(knn')|^2 \frac{\delta(\epsilon_{k+q,n'})\delta(\epsilon_{kn})}{N(E_F)^2}, \quad (2)$$

$$g_{q\nu}(knn') = \left(\frac{\hbar}{2M\omega_{q\nu}}\right)^{1/2} \langle \psi_{n\mathbf{k}}^0 | \hat{\epsilon}_{\mathbf{q}\nu} \cdot \frac{\delta V}{\delta \hat{u}_{\mathbf{q}\nu}} | \psi_{n'\mathbf{k}+\mathbf{q}}^0 \rangle, \quad (3)$$

a much larger  $(8 \times 8 \times 8)$   $\mathbf{k}$ -point sampling was used. In Eq. (2), the origin of the electronic energies ( $\epsilon_{kn}$ ) is taken to be the Fermi energy  $E_F$ .

Our system consists of a diamond  $(3 \times 3 \times 3)$  supercell (54 atoms) with one B atom in substitution (noted  $\text{BC}_{53}$  in what follows). We are thus in a 1.85% doping limit, close to the  $(2.5 \pm 0.5)\%$  studied experimentally. Upon structural relaxation, the B-C bond length is 1.57 Å as compared to the 1.54 Å for the C-C bonds in undoped

diamond (LDA values). The distance between second and third carbon neighbors is reduced to 1.52 Å in order to accommodate the larger B-C bonds.

We first explore the electronic properties and compare the band structure of BC<sub>53</sub> with that of diamond (see Fig. 1). We are clearly in a metallic regime with  $E_F$  located at  $\sim 0.54$  eV below the top of the valence bands. Even though Fig. 1 seems to confirm the model of rigid band doping around  $E_F$ , clear differences exist, in particular at the zone boundaries where degeneracies are left due to the reduction of the periodicity under doping. We note that in most directions, the band structure of pure and B-doped diamond start to significantly depart from each other precisely below  $E_F$ .

We also calculate the density of electronic states (eDOS) projected onto the atomic orbitals. Even though the eDOS projected onto the B orbitals (eDOS<sub>B</sub>) is small, it is instructive to plot [Fig. 1(b)] the ratio  $N_a \times \text{eDOS}_B / \text{eDOS}$ , where  $N_a = 54$  is the number of atoms per unit cell. Clearly, close to  $E_F$ , the relative weight of B orbitals is much larger than the weight on any given carbon atom. This ratio increases where the bands of the ideal and doped diamonds differ most significantly. The projection of the eigenstates onto the atomic orbital basis shows that the leading coefficients are the ( $p_x, p_y, p_z$ ) B orbitals. Such results indicate that even though degenerate with the diamond Bloch states, the wave functions of interest for  $e$ -ph coupling exhibit some degree of localization around the B atom.

We now study the phonon states at  $\Gamma$ . The related DOS ( $p$ DOS) is shown in Fig. 2(b) and compared in Fig. 2(a) to the one of undoped diamond [12]. As compared to the virtual-crystal approach, we do not observe the very large softening of the zone-center phonon modes predicted in

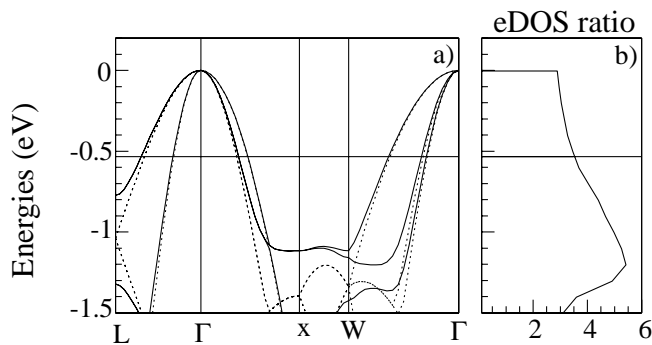


FIG. 1. (a) Details of the top of the valence bands along high-symmetry directions of the fcc BZ for undoped diamond in the  $(3 \times 3 \times 3)$  cell (dotted lines) and the doped BC<sub>53</sub> system (solid lines). The horizontal line is the position of the Fermi level in the doped case. The two band structures have been aligned at the top of the valence bands. (b) Ratio of the density of states projected onto the B orbitals to the total density of states per atom in the unit cell (this ratio has been set to zero in the band gap).

Ref. [6]. However, the splitting of the highest diamond mode [Fig. 2(a)] clearly results in transferring spectral weight to lower energy. This can be interpreted on the average as a softening of the optical frequencies. In particular, zone-center modes emerge around  $1200 \text{ cm}^{-1}$  [Fig. 2(b)] which are consistent with the appearance of new broad peaks in Raman experiments [1,13] around  $1220 \text{ cm}^{-1}$ .

More insight can be gained by calculating the  $p$ DOS projected onto the B atom and its four C neighbors (thick line). The most salient feature is that the new modes (threefold) at  $1024 \text{ cm}^{-1}$  (vertical dotted lines in Fig. 2) project to more than 50% on these five atoms. The analysis of the associated eigenvectors clearly indicates that these three modes (noted B modes) correspond to the stretching of the B to neighboring C atom bonds. The displacement of the B atom is  $\sim 22\%$  larger than that of C neighbors as expected from the difference in masses. Therefore, the dopant atoms induce vibrational modes

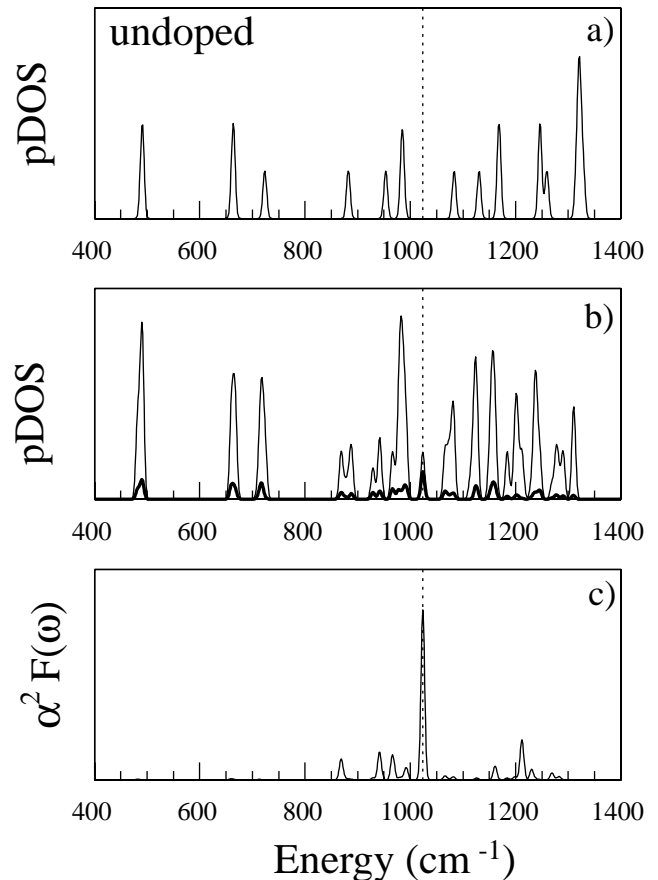


FIG. 2. Phonon density of states  $p$ DOS for (a) bare diamond with modes on an unshifted  $(3 \times 3 \times 3)$  grid, and (b) the boron doped BC<sub>53</sub> cell with modes at  $\Gamma$ . In (c) the spectral function  $\alpha^2 F(\omega)$  is represented for modes at  $\Gamma$ . Energies are in  $\text{cm}^{-1}$  and the  $y$ -axis magnitude is arbitrary. A  $5 \text{ cm}^{-1}$  broadening has been used. The vertical dotted lines indicate the energy position of the threefold B-related vibrational modes.

which are very localized in space. This is a significant deviation from a virtual-crystal approach where only extended phonon states can be evidenced. The influence of such modes on the  $e$ -ph coupling is now shown to be crucial.

We follow Eqs. (1)–(3) to calculate  $\lambda$ . With our limited  $\mathbf{q}$ -point sampling [14], we find that  $\lambda(q = \Gamma)$  is rather sensitive to the Gaussian broadening used to mimic the  $\delta$  functions in Eq. (2). However, such a variation is primarily related to the variation of the nesting factor  $n(q)$  [obtained by setting  $g_{q\nu}(knn')$  to unity in Eq. (2)]. This factor  $n(q)$  is a measure of phase space availability for electron scattering by phonons. Indeed, one verifies that the quantity  $\lambda(q)/n(q)$  ( $q = \Gamma$ ) is much more stable and displays a plateau over a large energy broadening range. We thus define an averaged  $\lambda$  by rewriting

$$\begin{aligned}\lambda &= \int d^3q \lambda(q) \\ &= \int d^3q n(q) \lambda(q)/n(q) \sim [\lambda(\Gamma)/n(\Gamma)] \int d^3q n(q) \\ &= N(E_F)^2 \lambda(\Gamma)/n(\Gamma).\end{aligned}$$

Such an approximation relies on the usual assumption that the  $e$ -ph matrix elements are varying much more smoothly as a function of  $\mathbf{q}$  than the nesting factor.

We find  $\lambda = 0.43 \pm 0.01$ . Such a value of  $\lambda$  is much smaller than that of  $\text{MgB}_2$  [in the absence of anharmonic effects [15],  $\lambda(\text{MgB}_2) \sim 1$ ]. Assuming now that the McMillan expansion [16] is valid in the limit of degenerate semiconductors:

$$T_C = \frac{\hbar\omega_{\log}}{1.2k_B} \exp\left[\frac{-1.04(1 + \lambda)}{\lambda - \mu^*(1 + 0.62\lambda)}\right]$$

and with a logarithmic averaged phonon frequency  $\omega_{\log}$  of  $1023 \text{ cm}^{-1}$ , the screening parameter  $\mu^*$  needed to reproduce the 4 K experimental value of  $T_C$  is found to be of the order of 0.13–0.14. This is a very standard value, indicating that phonon-mediated pairing mechanisms can adequately account for the superconducting transition in impurity-doped diamond [17].

With  $N(E_F) = 20.8$  states/spin/Ry/cell, the  $e$ -ph potential  $V_{ep}$  is  $280 \pm 10$  meV. Such a value is comparable to what was found in the Li-doped carbon clathrates ( $V_{ep} \sim 250$  meV [4]) and much larger than the 60–70 meV found for the fullerenes [18]. This was analyzed in terms of the amount of  $sp^3$  character of the C-C bonds [3]. For sake of comparison with Refs. [6,7], we calculate the deformation potential  $D$  such that  $\lambda = N_2 D^2 / M \omega^2$ , where  $N_2$  is the eDOS in eV/state/spin/“2 atoms cell.” With  $N_2 = 0.057$  and  $\omega = 1023 \text{ cm}^{-1}$ , one finds  $D = 27 \text{ eV}/\text{\AA}^{-1}$ , larger than the  $D \sim 21 \text{ eV}/\text{\AA}^{-1}$  value found in the virtual-crystal approximation [6,7]. This value is more than twice as large as the one calculated for  $\text{MgB}_2$ , indicating that it is primarily the low density of states at

the Fermi level, related to the 3D nature of diamond, that is responsible for the low value of  $\lambda$  and  $T_C$ .

Better  $\mathbf{q}$ -point sampling and the influence of anharmonicity [6,15] will certainly change the value of  $\lambda$ . Beyond the numerical estimates, it is important to look at the spectral decomposition of  $\lambda$ , that is, the Eliashberg function  $\alpha^2 F(\omega)$  [Fig. 2(c)]:

$$\alpha^2 F(\omega) = \frac{1}{2} \sum_{\mathbf{q}\nu} \omega_{\mathbf{q}\nu} \lambda_{\mathbf{q}\nu} \delta(\omega - \omega_{\mathbf{q}\nu}). \quad (4)$$

By comparison with the  $p$ DOS, it appears that a significant contribution to  $\lambda$  comes from the B-related phonon modes. As a matter of fact, these three modes contribute to about 50% of the coupling [19]. In particular, the resulting Eliashberg function is very peaked at the impurity vibrational modes energy, displaying the  $\delta$ -like shape of an Einstein model. The strong  $e$ -ph coupling with the B modes should be seen experimentally as an increase of the inverse lifetime of phonons in neutron spectroscopy [20] around  $1023 \text{ cm}^{-1}$ .

The importance of local modes was first proposed to understand the physics of high- $T_C$  ceramic compounds [21]. However, in such systems, it is low-energy acoustical phonons which are believed to enhance the coupling. In the present case, the B modes are of medium-energy optical character and the large value of  $\lambda$  is not driven by phonon energy softening. As another reference system, the  $C_{60}$  on-ball modes responsible for superconductivity in fullerenes could also be considered as localized vibrational states. However, such modes are not dopant related and the low-energy alkali-atom vibrations hardly contribute to  $\lambda$  in the fullerene case. This is in significant contrast with the present case where the dopant atoms provide both the charge carriers and the localized phonons responsible for a significant fraction of the  $e$ -ph coupling.

To strengthen that point, we look at the superconductivity of diamond within a rigid band model [22]. We plot in Fig. 3 the evolution of  $\lambda$  as a function of the position of the Fermi level. For  $E_F$  located  $\sim 0.5$ – $0.6$  eV below the

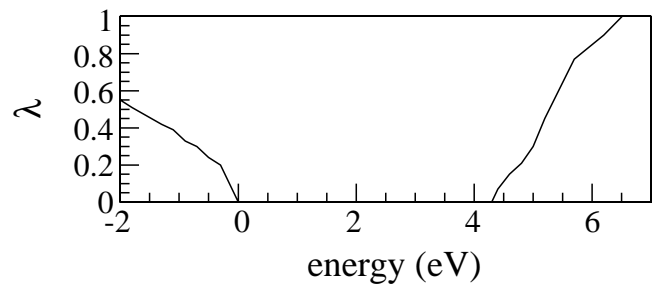


FIG. 3. Evolution of  $\lambda$  for diamond, doped within a rigid band model (see text), as a function of the Fermi energy position  $E_F$ . The energy reference has been set to the top of the valence bands.

top of the valence bands, we find a  $\lambda$  of  $\sim 0.24$ , that is roughly 55% of what we find in the  $\text{BC}_{53}$  case. Even though very qualitative, this computer experiment substantiates the conclusion that B-related modes contribute significantly to the  $e$ -ph coupling. Further, Fig. 3 clearly suggests that larger  $\lambda$  could be achieved under larger doping conditions due to the quadratic rise of  $N(E_F)$  as a function of  $E_F$ .

Finally, to connect with upcoming experimental studies of the role of boron, we look at the influence of B-isotope substitution. From  $^{10}\text{B}$  to  $^{11}\text{B}$ , the B modes shift down by  $\sim 9 \text{ cm}^{-1}$ , which is well within experimental resolution. Both lifetime shortening and isotopic shift should be a mean to experimentally identify the dopant modes and the strength of their coupling. As expected,  $\lambda$  is mass independent. Assuming that the change in  $T_C$  follows that of the  $\omega_{\log}$  prefactor in the McMillan formula [23], we calculate the B-related partial isotope coefficient  $\alpha_B = -d \ln T_C / d \ln (M_B)$  to be  $\sim 0.08$ . As  $T_C$  is small, this value may be beyond experimental resolution. The signature of the dopant vibrational modes could also be studied by transport experiments (e.g., thermopower) or phonon Raman scattering.

In conclusion, we have shown that the role of boron in doped diamond is unconventional in that a significant fraction of the coupling coefficient  $\lambda$  originates in vibrational modes very localized on the defect centers [24]. With a  $\lambda$  of 0.43, much smaller than that of  $\text{MgB}_2 \sim 1$ ,  $T_C$  remains small. Even though the  $e$ -ph potential is extremely large, the 3D nature of the network reduces the density of states at the Fermi level. This invites one to study the case of doped diamond surfaces where both the contraction of the reconstructed bonds and the 2D nature of the surface states may lead to larger  $T_C$  [25].

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