RD42 Note N0.15

# Effect of Lapping of CVD Diamond

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The material removal study reported in the latest Report on DeBeers Samples, No. 4/2000 provides an intriguing opportunity for studying the empirical charge transmission properties of CVD diamond. It not only would have implication on the long speculated “linear model” but also could provide information on whether the signal we have been measuring comprises of two charge carriers.

## INTRODUCTION

Results of material removal study have been reported in the Report on DeBeers Samples, No. 4/2000 recently. The numerical data and a plot of the measured collection distance against the final thickness are shown for DB-91 and DB-92. Although the measurement so far is for three thickness values each but already it is worth examining carefully.

“Linear model” which is consistent with our intuitive picture of crystalline growth of CVD diamond has long been speculated based on the measurement of charge collection distances of many samples accumulated in the past that indicated seemingly linear dependence of the charge collection distance on the thickness of the samples.

On the other hand an explicit formulation of the linear model has been attempted. D. Fish developed a Monte Carlo program, and we have previously reported an analytical formula resulted from a proper integration over the charge deposition and transmission. The model assumes a local exponential factor whose charge absorption length is linearly proportional to the depth measured from the original substrate surface.

In the following we compare the reported data with the prediction of such explicit “linear model” calculation and discuss the implication.

Such study is not only of an academic interest, it has a significant impact on the economy of the detector grade CVD diamond samples. If we find a correct model that describes the dependence of the transmission growth on the crystalline growth, we will be able to optimize the desire of obtaining large collection distance with regard to the economy of growing rather thick CVD diamond and lapping it down both of which are not quick process.

## MODEL FORMULATION

### General formalism

The detail is reported in RD42 Note No 13.

Charge $dQ_{induced}$ induced on a parallel plate electrode by a local motion of a charge along a uniform field in CVD diamond detector is a product of the deposited charge $dQ_{deposited}$ and the distance of travel $dz$ normalized by the distance $D$ between two electrodes.

$$dQ_{induced} = dQ_{deposited} \bullet \frac{dz}{D} \quad . \tag{1}$$

Here an implicit assumption is that the parallel plate electrode is infinitely wide. However such assumption is a good approximation for the electrodes of a lateral diameter of ~2$D$ or greater, a condition well satisfied in actual diamond detector.

$D$ is the final thickness and if the material is lapped from the substrate side by depth $T_0$ from originally grown thickness $T$, then

$$D = T - T_0 \quad . \tag{2}$$

Therefore the total induced charge is a result of an integration of (1) over the position of the charge deposition and the length of the travel of the charge with proper charge absorption factor $f_{abs}$ coming from the inherent charge absorption. The travel of the charge is from the deposited point z' to the end of the travel $T$ with the absorption factor dependent on the path from the deposited point z' and the point where the charge is travelling. Taking the case in which the charge carrier is traveling towards growth side away from substrate side,

$$Q^{total}_{induced} = \frac{1}{D}\int_{z=z'}^{T}\int_{z'=T_0}^{T} \frac{dQ_{deposited}}{dz'} f_{abs}(z,z')dz'\,dz \quad . \tag{3}$$

### Infinite transmission

If there is no charge absorption,

$$f_{abs}(z,z') = 1. \tag{4}$$

Then (3) trivially becomes

$$Q^{total}_{induced} = \frac{1}{D} \bullet (Q_0\ D) \bullet \langle travel\ distance \rangle_{mean}$$

$$= \frac{Q_0\ D}{2} \tag{5}$$

since the geometrical average of travel distance is half of the thickness $D$. Here $Q_0$ is the electron charge $e$ times the average number of charge carriers, *electrons* or *holes*, released per unit length traversed by an incident charged particle :

$$Q_0 = \frac{dQ_{deposited}}{dz'} \quad . \tag{6}$$

Thus the collection distance $D_c$ defined as

$$D_c = \frac{Q_{measured}}{Q_0}$$

becomes $= \dfrac{D}{2}$ . ( single charge carrier upper limit ) (7)

This is the absolute upper limit independent of the model.

Note that in the definition of the collection distance, we customarily use the electron charge $e$ times the number of *e-h* pairs per unit length, 36 $e$ / μm, as $Q_0$. <u>Therefore if both of the charge carriers</u>

are equally contributing, the collection distance $D_c$ is twice the above and must be equal to the thickness $D$ :

$$D_c \quad = \quad D \qquad\qquad \text{(two charge carrier upper limit)} \qquad\qquad (8)$$

It is useful to remind ourselves the implication of what we are observing routinely . A sample of 500 µm should give a collection distance of 500 µm if there is no charge absorption if we assume an equal contribution from electrons and holes with an average transmission of 250 µm coming from geometrical limit. However we are observing collection distance of ~200 µm which means that the average transmission is only ~100 µm for each of electrons and holes most likely bound by the absorption, not by the geometrical boundary .

**Uniform charge absorption**

As described in RD42 Note No. 13, it is easy to formulate the case of uniform charge absorption. With a constant charge absorption length $\lambda_0$, an exponential absorption factor

$$f_{abs}(z,z') \;=\; \exp\left( -\frac{z-z'}{\lambda_0} \right) \qquad (9)$$

needs to be integrated over $z'$ and $z$ through the total thickness $D$. Whether it was lapped or not is irrelevant. Then carrying out the integration, the collection distance is :

$$D_c = \lambda_0 \left[ 1 - \frac{\lambda_0}{D} \left\{ 1 - \exp\left( -\frac{D}{\lambda_0} \right) \right\} \right] \quad .\text{( single charge carrier )} \qquad (10)$$

Note that this is for a single charge carrier and if the electrons and holes are both contributing, the above needs to be multiplied by 2.

**Linear model**

The local charge absorption must have a form of an exponential as

$$\exp\left( -\frac{dz}{\lambda(z)} \right) \qquad (11)$$

as the deposited charge travels a small distance $dz$ at a distance $z'$ measured from the original substrate side surface. The attenuation over a path length from the deposited point $z'$ and the point of the travel $z$ is then

$$f_{abs}(z,z') \quad = \quad \exp\left\{ -\int_{l=z'}^{z} \frac{dl}{\lambda(l)} \right\} \quad . \qquad (12)$$

Then we assume that the charge absorption length $\lambda(z')$ is proportional to the distance $z'$ from the substrate side surface:

$$\lambda(z') = c\, z' \qquad (13)$$

with a constant $c$ , a coefficient that represents the charge transmission characteristics of each sample. With such simple assumption, the above integral becomes

$$-\int_{l=z'}^{z} \frac{dl}{\lambda(l)} \quad = \quad \ln\left( \frac{z'}{z} \right)^{\frac{1}{c}} . \qquad (14)$$

Therefore

$$f_{abs}(z,z') \quad = \quad \left(\frac{z'}{z}\right)^{\frac{1}{c}} \tag{15}$$

Carrying out the integration of eq. (3) with the above formula over the deposited point $z'$ and the longitudinal path $z$,

$$Q_{induced}^{total} = Q_0 T \;\; f(c, \frac{T_0}{T}) \; . \tag{16}$$

with a universal dimensionless factor $f(c, \frac{T_0}{T})$ with a parameter $c$ and a dimensionless quantity $\frac{T_0}{T}$:

$$f(c, \frac{T_0}{T}) = \frac{1}{\left(1-\frac{1}{c}\right)\left(1+\frac{1}{c}\right)} \frac{1}{1-\left(\frac{T_0}{T}\right)} \left[ \frac{1}{2}\left\{1+\left(\frac{T_0}{T}\right)^2\right\} - \frac{1}{2c}\left\{1-\left(\frac{T_0}{T}\right)^2\right\} - \left(\frac{T_0}{T}\right)^{1+\frac{1}{c}} \right] .$$

( single charge carrier ) (17)

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The above is exactly the same for either case of the deposited charge traveling away from the substrate side or towards the substrate side. Therefore <u>if the electrons and holes are contributing equally, the above formula needs to be multiplied by 2.</u> Note again that $Q_0$ is defined as the charge for one type of carriers, 36 $e$ /µm.

The charge collection distance $D_c$ is then expressed as :

$$D_c \quad = T \bullet f(c, \frac{T_0}{T}) \qquad \text{( single charge carrier )} \tag{18}$$

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correctly having the dimension of length.

If there is no lapping on the substrate side, then $T_0 = 0$ and

$$D_c \quad = \quad \frac{T}{2\left(1+\frac{1}{c}\right)} \qquad \text{(No substrate side lapping, single charge carrier)} \tag{19}$$

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is <u>proportional to $T$</u> .

The formula, in turn, can be used to find the coefficient $c$ from measured values of $D_c$ and $T$ if there is no prior lapping.

$$c \quad = \quad \frac{2D_c}{T-2D_c} \qquad \text{( No substrate side lapping, single charge carrier ) .} \tag{20}$$

For two charge carriers, (19) and (20) are replaced by:

$$D_c \quad = \quad \frac{T}{\left(1+\frac{1}{c}\right)} \qquad \text{( No substrate side lapping, two charge carrier )} \tag{21}$$

$$c \quad = \quad \frac{D_c}{T-D_c} \qquad \text{( No substrate side lapping, two charge carriers ).} \tag{22}$$
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## COMPARISON WITH DATA OF MATERIAL REMOVAL STUDY

**Measured data**

The data reported in the Report on DeBeers Samples No. 4/2000 are for DB-91 and DB-92. From the Report the measured collection distances are listed in Table 1.

As seen in the plot in the Report, DB-91 data points show almost linear increase of the collection distance with increasing thickness while in case of DB-92, the collection distance decreases with the thickness.

Table 1 Measured data from study on material removal . From Report on DeBeers Samples No. 4/200

| | Thickness | Measured collection distance (Average of "marked side up" and "marked side dn" data) |
|---|---|---|
| DB-91 : | 800 μm | 169.5 μm |
| | 660 | 143 * |
| | 570 | 127.5 |
| DB-92 : | 780 μm | 162 μm |
| | 630 | 172 |
| | 560 | 197.5 |

* The point for 600 μm in the plot in the Report seems to be wrong possibly due to miscalculation of the average.

**Comparison with uniform charge absorption prediction**

We compare the predicted behavior based on uniform charge absorption case. As discussed in detail in RD42 Note. No13, the general trend of the formula (10) is a monotonic but gradually saturated increase of the collection distance with the thickness.

In Fig. 1 the calculated curves were drawn through 800 μm point of DB-91. Naturally there is no distinction on which side was lapped. The value of the constant absorption length is 96.4 μm for the two carrier case and 237.7 μm for single carrier case. Obviously the calculated curves poorly reproduce the trend of the data points and therefore it is safe to conclude that the uniform charge absorption model is disfavored.

Straight lines from the origin is the absolute upper limit of infinite transmission for single and two carrier cases independent of the model, as derived in (7) and (8).

Also a line was drawn from the origin through T= 800 μm point of DB-91 to guide the eyes. This line corresponds to the case of no substrate side lapping in linear model, as described later.

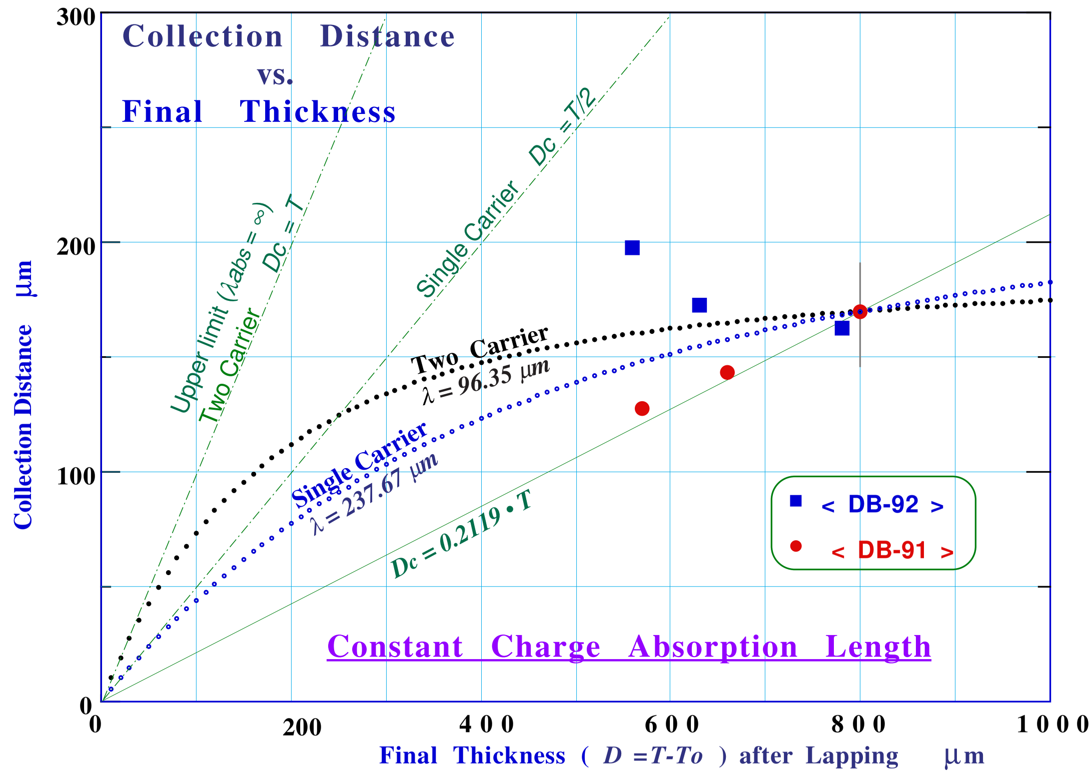


Fig. 1. Comparison of the prediction of uniform charge absorption with material removal data. The measured data points are from the Report on DeBeers Samples No. 4/2000. The curves are drawn through the 800 μm point of the data of DB-91.

**Comparison with explicit linear model**

**a) Single charge carrier**

Since the collection distance of DB-91 decreases almost linearly with decreasing thickness, one can easily figure out, consulting with the general trend shown in the graphs in RD42 Note No.13, that the lapping is made on the growth side. In order to compare the values calculated by the explicit linear model formula with these data points, one needs to know the value of the coefficient *c*. We calculate two values, one for the case of no prior lapping on substrate side after growth and the second assuming a *prior* removal from the substrate side.

If there was nor prior substrate side lapping, from (20) derived in the previous section, the coefficient c is determined to be

$$c = 0.2688$$

using the point of $D_c$ =169.5 μm at $T$ = 800 μm, and the collection distance must increase with T as in (19) as:

$$D_c \quad = \quad 0.2119 \bullet T .$$

If we assume some lapping prior to the test, we use the three data points of DB-91 that lie neatly on a straight line, taking correct average values of two measurements listed in the Report. seemingly without having gross error, to determine the values of coefficient *c* . By fitting the three points requiring that those have common value of *c* and the same thickness was removed by prior lapping on the substrate side, we have come up with the values listed in Table 2 using formula (18).

Table 2. Values of coefficient *c* calculated from DB-91 data points. Single charge carrier was assumed.

| | | | | |
|---|---|---|---|---|
| DB-91 | Assuming no *prior* lapping | : | $T_0$ = 0 μm | $c$ = 0.735 |
| | Assuming *prior* lapping - Fit to three points | : | $T_0$ = 90 μm | $c$ = 0.544 |

( $T_0$ : Thickness removed from substrate surface by *prior* lapping. )

Since the data points for DB-92 is significantly scattered, we use the same values of *c* listed above to calculate the collection distances for the case of lapping substrate side.

Fig. 2 is the plot of the resultant curves based on these values of *c* overlaid on the plot of the measured data points from the Report.

In the figure, the curve for growth side lapping with $T_0$ = 90 μm well fit the three points of DB-91 although the difference from the straight line of $T_0$ = 0 μm is not significant. The curves that rise from zero point and then fall before reaching the end points are for the case in which the material is removed from substrate side. The data points for DB-92 are likely to be the case in which the material was removed from substrate side but seem to be scattered and the fit by the calculation is poor. It might be speculated that it is because the substrate side is significantly irregular with inclusions and voids and when the material was removed in the study, gross defects might have been removed making abrupt improvements.

The two points of thicker final thickness are close to the calculated curves. However one can make an argument that it is more natural to expect the measured data points to be lower, not higher, than what they ought to be due to local defects. Therefore the fact that the third point at *D* = 560 μm is much higher than the curves can be interpreted as an indication that the assumption of single charge carrier is not plausible.

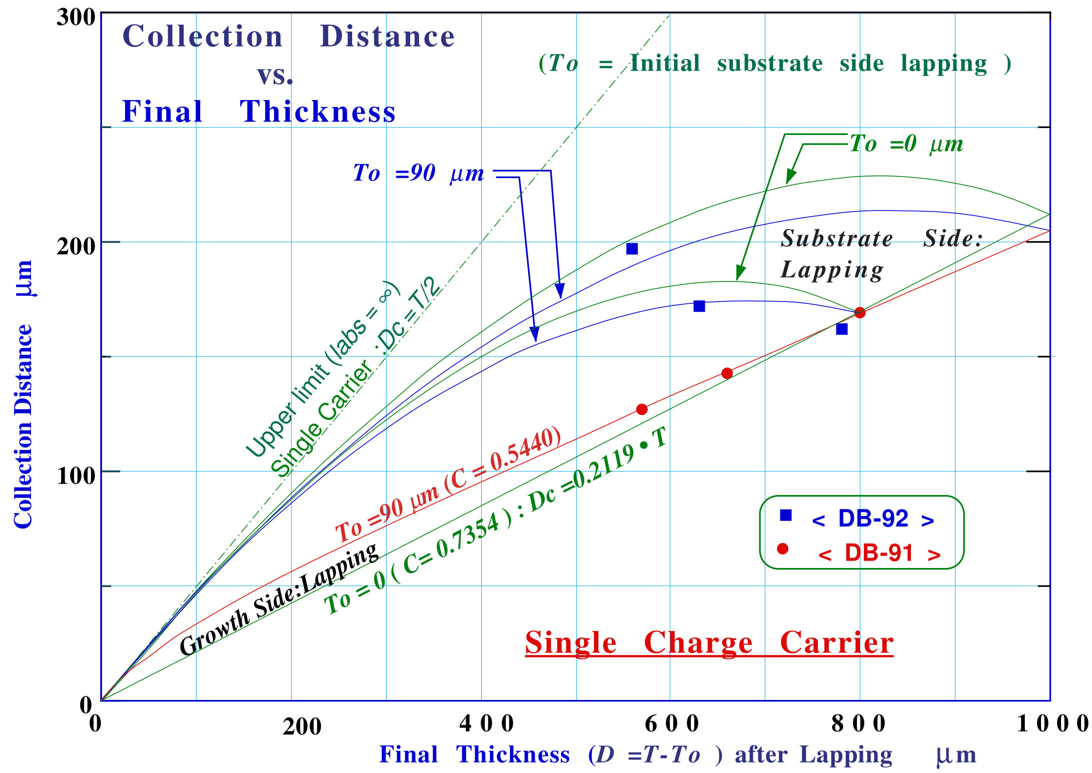


Fig. 2. Comparison of the linear model prediction with the measured data of material removal. Measured data points are from the Report on DeBeers Samples, No. 4/2000. Curves were calculated based on explicit linear model assuming single type of charge carriers, electrons or holes .

**b) Two types of charge carriers, electrons and holes.**

If we assume equal contributions from electrons and holes, the fit to the measured points of DB-91 is exactly the same for the case of no prior lapping on substrate side as for single charge carrier,

$D_c = 0.2119 \bullet T$

although the value of the coefficient c is now

$c = 0.2688.$

If there is prior lapping on the substrate side, the three points favor

$T_0 = \sim 90$ with $c = 0.220$

but the $D_c$ vs. $T$ relationship is only slightly different from single charge carrier case. The parameters are summarized in Table 3.

Table 3. Values of coefficient $c$ calculated from DB-91 data points. Equal contributions from two types of charge carriers, electrons and holes, was assumed.

| | | | |
|---|---|---|---|
| DB-91 | | | |
| Assuming no prior lapping | : | $T_0 = 0$ µm | $c = 0.2688$ |
| Assuming prior lapping- Fit to three points | : | $T_0 = 70$ µm | $c = 0.220$ |

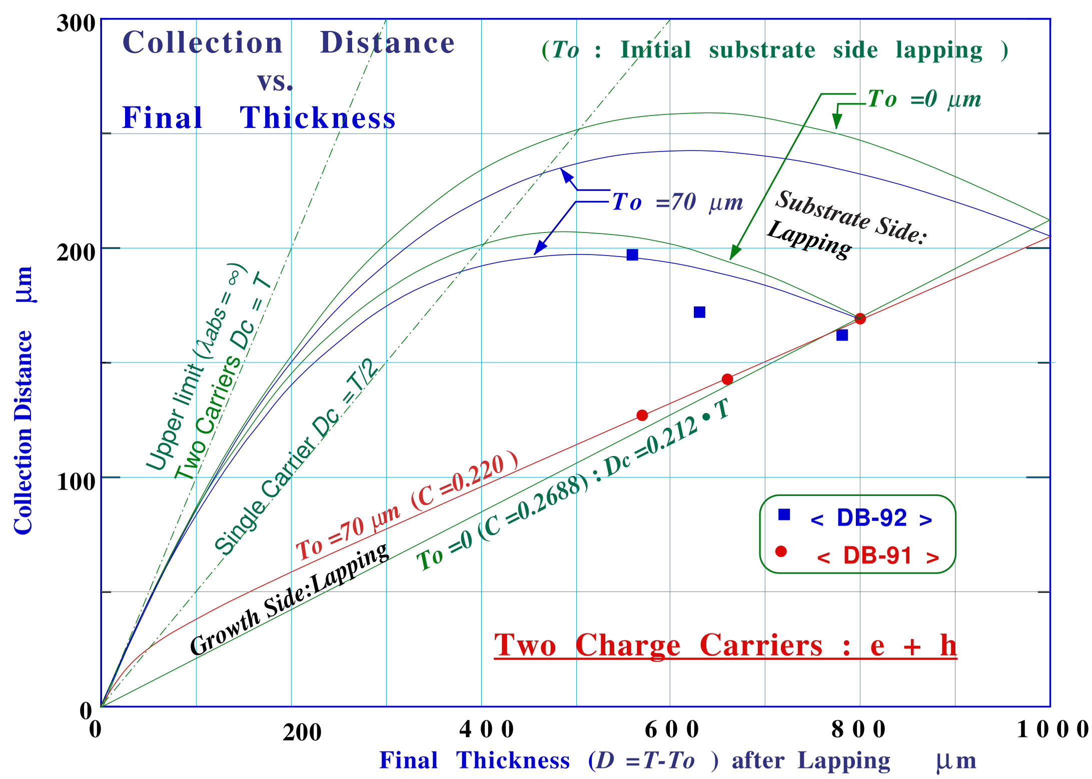


Fig. 3. Dependence of the charge collection distance on the final thickness after the material was removed from the surface. Measured data points are from the Report on DeBeers Samples, No.4/2000. Curves were calculated based on the explicit linear model assuming two types of charge carriers, electrons and holes.

In Fig, 3, we compare the calculated curves with the measured data points. The fit of the curve to the data of DB-91 for $T_0$ = 90 µm is excellent although the difference from the straight line for $T_0$ = 0 µm is marginal. The fit to the measured points of DB-92 is still problematic although the curve is now close to the third points for the thickness of 570 µm, indicative of that two charge carrier assumption is a plausible one. Lapping both of the samples to 300 to 400 µm will test the validity of the explicit linear model. Also it will be a crucial test of whether the observed signals are consistent with single charge carrier or two charge carrier type because if the explicit linear model holds the curves are going to intercept the absolute upper limit of single charge carrier case independent of the model.

Within the limited scope of the data points, it is obvious that the explicit linear model is far better favored than the constant absorption length model to describe the trend of the data especially for the case of growth side lapping.

The curves are also drawn for the case of the D=1000 µm, as suggested by H. Kagan at the RD42 meeting at Rutgers University to see what kind of improvement we can expect. With a caveat in mind that there is no guarantee that the charge transmission in CVD diamond continues to grow linearly as the linear model assumes beyond what is observed in these data, it is amusing to see a possibility of achieving a collection distance of the order of 240 µm for the final thickness of 500 µm.

## DESIRABLE TEST

It is an interesting exercise to think of a possible study to critically test the concept of linear model and whether single or two carrier types are involved.

A possible scenario is graphically shown in Fig. 4. Three cases of *prior* substrate side lapping, 0, 200, and 400 µm were plotted for the test lapping of both the growth side and the substrate side with two charge carrier being assumed. Unless otherwise noted, the curves are for $c$ = 0.220 which is the smaller, therefore conservative, value of the coefficients fitted to DB-91 as derived in Fig.3. Straight lines between the origin and the endpoints of maximum thickness corresponds to zero prior lapping. However, except for lowest line for $T_0$ = 0, the values of c is unrealistically high and the lines are to be taken as guide to see the deviation of the prediction for growth side lapping from straight line for no prior lapping.

The *non-linear* decrease of the collection distance with lapping the growth side is much enhanced when the much deeper prior lapping is made. Also the test on the extent of the "linear" growth of the transmission along with the crystalline growth is an interesting subject. Therefore it is desirable to extend the test to $D\approx$1000 µm range for which *as-grown* thickness $T$ needs to be beyond 1000 µm.

Again lapping the sample on the substrate side down to half of the as-grown thickness will provide a crucial data on whether we are observing two types of charge carriers.

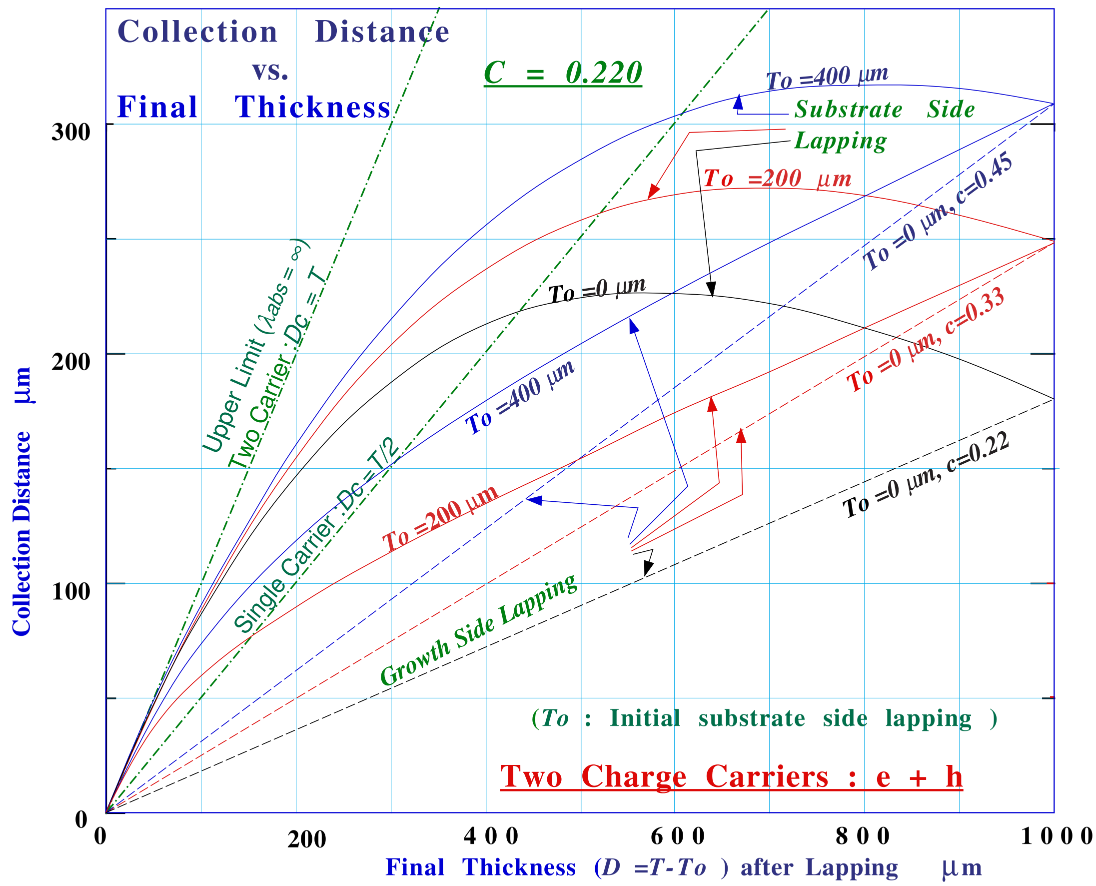


Fig. 4. Possible test of the material removal effect. $c = 0.22$ from the fit to DB-91 in Fig. 3 was taken unless otherwise noted. Straight lines between the origin and the end point at $D = 1000$ µm are the case of no initial lapping on substrate side. However, the two upper lines for $T_0 = 200$ µm and 400 µm correspond to unrealistically high value of $c$. and these lines are drawn to guide eyes to find the deviation of the curves of growth side lapping from straight lines.

## SUMMARY

Predictions based on
- uniform charge absorption,
- linear model assuming single charge carrier,
- linear model assuming two types of charge carriers,

have been compared with the material removal study reported in the Report on DeBeers Samples No 4/2000.

Uniform charge absorption model poorly reproduces the trend of the data points of either of DB-91 or DB92.

The data points of DB-91 are consistent with linear model predictions for lapping growth side with prior removal of 70 to 90 μm from substrate side although the difference from the case of no *prior* removal from substrate side is marginal. There is no significant distinction between single carrier assumption and two carrier assumption for DB-91 unless the sample is thinned down to 100 to 200 μm and the measurement accuracy is maintained at the level of what it appears to be in the reported test.

The data of DB-92 is more scattered but the trend of growing collection distance with thinning down the thickness is consistent with the prediction of the explicit linear model for the case of lapping substrate side. If we take a stance that the data points must be smaller, not greater, than the ideal case due to local gross defects, two charge carrier assumption is more plausible.

A distinctive test is predicted to be the measurement with continuing the lapping DB-92 to 300 to 400 μm. In such thickness the two charge carrier prediction is going to start falling from the level of ~200 μm observed at D = 560 μm and intecepts the absolute upper limit of single charge carrier assumption .

Similar test on a sample of much thicker as-grown thickness with much thicker prior lapping on substrate side will be very useful to test the validity of linear model. Also the extent of the "linearity" of the transmission growth is an interesting subject to be tested .

## REFERENCES

D. Fish, "Modelling Signal Generation in CVD Diamond Detectors".
M. Mishina, "Induced Charge on Diamond Detector", RD42 Note No. 13.