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Reply to comments on "Ti: sapphire crystal used in ultrafast lasers and amplifiers"

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This letter is intended as a reply to the comments of C.P. Khattak and F. Schmid directed to our original paper [1] which described the growth of large size, high quality Ti:sapphire crystals by temperature gradient technology (TGT) used in high peak power laser and amplifier systems. The important issue for growing large size, high quality Ti:sapphire crystal is to control the titanium concentration along the growth direction. The large size, high quality Ti:sapphire crystals can be grown by Heat exchange method (HEM) and temperature gradient technology (TGT). The growth orientation of Ti:sapphire crystal along $\langle 0001 \rangle$ is more difficult than growth along other orientations. The difficulty of growing $\langle 0001 \rangle$ oriented sapphire crystal is attributed to the weakened effect of the main glide system and the close packed direction along the $\langle 0001 \rangle$ orientation. The $\langle 0001 \rangle$ oriented sapphire crystal is the desirable orientation for minimizing birefringence and this orientation is used for many optical applications such as laser gain medium, windows, etc. Therefore, growth of $\langle 0001 \rangle$ oriented sapphire crystal would be more desirable to achieve better material utilization for high quality optical applications and reduce the cutting lose and cost from other oriented sapphire crystals.

Uniformly titanium distribution in the sapphire crystal is desirable for the laser applications, however, the segregation coefficient of titanium in sapphire is less than 0.2, so there is concentration gradient along the growth axis, and how to minimize the concentration gradient along the growth axis is very important for laser applications. The $\langle 0001 \rangle$ orientation Ti:sapphire crystals grown by TGT can reduce the concentration gradient along the growth axis and the distribution of titanium along the radius is nearly uniformly, therefore the whole piece of crystal cut from the Ti:sapphire crystal boule perpendicular to the $\langle 0001 \rangle$ orientation can be used as large-size amplifier media, the cost of fabricating Ti:sapphire samples is lower than those fabricated orthogonal to growth direction of $\langle 10\bar{1}0 \rangle$ or $\langle 11\bar{2}0 \rangle$ oriented boules. In Fig. 2 the comparison of the absorption coefficient along the growth axis are given and the result shows that the concentration gradient of TGT grown Ti:sapphire crystal along the growth axis is smaller than that of Ti:sapphire grown by HEM. Of course high concentration can be achieved by adding more dopant into the charge, but this will increase the concentration gradient along the growth axis, which will result in worsening the optical properties and mechanical properties. And the most important thing is how to grow high concentration Ti:sapphire crystals with high quality. Fig. 3 shows the comparison

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result of the Ti:sapphire crystal cw operation at room temperature without water cooling, for these two kinds of Ti:sapphire crystals, although the concentration of titanium in Ti:sapphire crystal grown by TGT is a little higher than that grown by HEM, the 15 mm length of the crystal is still long enough to absorb enough pump power (the difference of the absorbed pump power can be neglected), the comparison of such laser performance is reasonable.

It is well known that the quality of the crystal should be compared in the applications of the crystals, the customers are interested in the specified crystals they will use. The quality of crystals is varied even grown in the same furnace with the same growth parameters because there are some unpredicted factors will affect the crystal growth, the quality of the crystal is also varied in the same crystal boule owing to the defects accompanying with the growth, the main issue is to reduce the defects to realize the homogenious optical properties for growth of large-size and high quality Ti:sapphire crystals.

Here we appreciated Dr. Khattak's information that large size $\langle 0\,0\,0\,1\rangle$ oriented Ti:sapphire bouldes are grown by HEM and large-size, high quality $\langle 0\,0\,0\,1\rangle$ oriented Ti:sapphire crystal fabricated orthogonal to $\langle 1\,0\,\bar{1}\,0\rangle$ or $\langle 1\,1\,\bar{2}\,0\rangle$ growth direction are commercialized. We will take more effort to improve the growth technology of TGT to produce large size high quality sapphire crystals.

References

[1] Jun Dong, Peizhen Deng, Ti: sapphire crystal used in ultrafast lasers and amplifiers, J. Crystal Growth 261 (2004) 514.