Temperature dependence of the hyperfine fields of $^{111}$In in sapphire (Al$_2$O$_3$) single crystals

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Michael Steffens$^1$ Jakob Penner$^1$ Hassan Kamleh$^2$
Reiner Vianden$^1$

$^1$Helmholtz - Institut für Strahlen- und Kernphysik, Universität Bonn, Germany

$^2$Department of physics, Faculty of sciences, University of Damascus, Syria
Introduction

- Basing on previous measurements of undoped $\text{Al}_2\text{O}_3$
  
  *Penner and Vianden, Hyperfine Interactions 158(1), 389 (2004)*

- Temperature dependent measurements of the electric field gradient (EFG) in doped $\text{Al}_2\text{O}_3$

- Experimental technique: time-differential perturbed angular correlation (TDPAC)

- Investigation of the ”electron capture after effect”

- Possible application: electron mobility studies in semiconductors and insulators
Electron capture decay of $^{111}$In

$(p) + e^- \rightarrow (n) + \nu_e$

Half life of the (highly) ionized state depending in the electronic surrounding

- vacuum: $t_{1/2}$ large
- metallic: $t_{1/2} \approx 10^{-12}$ s
- insulating: $t_{1/2} \approx 10^{-9}$ s, influenced by electron mobility and density
Experimental technique: TDPAC

$t_{1/2} = 2.73$ $d$
$t_{1/2} = 0.12$ $ns$
$t_{1/2} = 85$ $ns$
$Q_{5/2} = 0.83(13)$ $b$

Hyperfine interaction of the EFG with the nuclear quadrupole moment $Q$

$\Rightarrow$ Quadrupole interaction frequency $\nu_Q = \frac{eQV_{zz}}{\hbar}$
Material:
(0001) oriented single crystals
(5 × 5) mm² pieces from a 2” × 430 µm wafer
≈ 99.9999% purity

Lattice parameters:
\(a = 4.75 \text{ Å}, c = 12.99 \text{ Å}\)

Bandgap = 9.9 eV
$^{111}$In in undoped Al$_2$O$_3$

- Ion implantation of $^{111}$In at BONIS (BONn Isotope Separator)
- Rapid thermal annealing ($T_a = 1273$ K, 2 min, N$_2$-flow)
Temperature dependence of the EFG in doped Al$_2$O$_3$

- Co-implantation with overlapping implantation profile

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Fluence (atoms/cm$^2$)</th>
<th>Effective charge subst. Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{111}$In / $^{111}$Cd</td>
<td>160</td>
<td>$10^{12}$</td>
</tr>
<tr>
<td>Cr</td>
<td>80</td>
<td>$10^{13}/10^{14}$</td>
</tr>
<tr>
<td>Mg</td>
<td>40</td>
<td>$10^{14}$</td>
</tr>
<tr>
<td>P</td>
<td>60</td>
<td>$10^{13}$</td>
</tr>
<tr>
<td>Si</td>
<td>50</td>
<td>$5 \cdot 10^{13}$</td>
</tr>
</tbody>
</table>

PAC probe nucleus

750 K

- In: 750 K
- In + Cr (1E13): 750 K
- In + Mg: 750 K
- In + P: 750 K

900 K (875 K)

- In: 900 K
- In + Cr (1E13): 900 K
- In + Mg: 900 K
- In + P: 875 K
- In + Si: 750 K
- In + Si: 900 K
Temperature dependence of $\nu_Q$

$$\nu_Q(T) = 228(2) \text{ MHz} - 1.6(3) \cdot 10^{-2} \text{ MHz/K} \cdot T$$
Temperature dependance of the static interaction $f_S$

In w/o co-implantation (1E12 ions/cm$^2$)
In + Si (5E13 ions/cm$^2$)
In + Mg (1E14 ions/cm$^2$)
In + P (1E13 ions/cm$^2$)
In + Cr (1E13 ions/cm$^2$)
In + Cr (1E14 ions/cm$^2$)

fraction $f_s$ [%]
sample temperature [K]
Characterization of the EFG in relation to the sample temperature in an insulator (Al$_2$O$_3$)

Changes of this relation following doping of Cr, Mg, P and Si
  
  - Minor temperature dependence of $\nu_Q$
  - Doping of Cr has a large impact at higher Cr fluences (fluence dependent effect)

Relaxation of the atomic shell of $^{111}$Cd after electron capture gives us information about the electron mobility and the conductivity of the insulator