Measurement of carbon concentration in silicon crystal/ 2-nd generation
(30) Solution of inner phonon band problem in infrared absorption (2) Liquid N-T measurement

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シリコン結晶中の低濃度炭素の測定/第二世代(30)赤外吸収の inner phonon band 対策、液体窒素温度測定
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IR absorption is practical as well as scientific measurement technique of carbon concentration in Si [1]. Low temperature measurement at liquid N T was dominant especially in early days [1, 2, 3] and adopted in the ASTM Standard [4], as summarized in Tab. Four representative papers were from single and poly-Si suppliers [2, 3, 5, 6] showing the easiness of measurement at liq. N T. Moreover in 2011, measurement on the Avogadro crystal for $2 \times 10^{14}/cm^3$ was reported [7]. It established as the base of science: Carbon concentration determines the accuracy of Avogadro number and International System of Units [8]. It was said that low T measurement is advantageous for phonon overlapping problem [7].

We have established RT measurement in 1987 [9] and the results consisted ASTM Standard prepared for FTIR in 1990 [4]. In 2005 we demonstrated measurement of $10^{14}/cm^3$ at RT [10]. In 2016 we identified the middle and inner phonon band problem at RT [11]. In 2018, we reported the LT measurement of $10^{13}/cm^3$ for single crystal [12]. 5 4mm thick samples with [C] lower than $1 \times 10^{14}/cm^3$ were measured, and differential absorption spectra of all pairs are shown in Fig. Though interference fringes are observed, the inner phonon bands do not interfere for most spectra. C concentration was obtained to be 10, 9, 6, 4, $1 \times 10^{13}/cm^3$, respectively. Instrumental detection limit (IDL, 3x standard deviation of measured difference from the expected value, [4, 13]) was about $1 \times 10^{13}/cm^3$ and spectral detection limit [13] was $2 \times 10^{13}/cm^3$, for this preliminary unoptimized measurement. IR enabled $10^{14}/cm^3$ measurement of poly-Si both at RT and LT, more sensitive at LT. Ratio between the absorption at RT and LT [14] must be redetermined using FTIR.

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	RT	Low T*	poly
1965 Newman		8x1016	
1968 Baker#		1.3x10^16	
1972 Endo	1x1017	1x1017	
1987 Inoue	2.8x1015		
FTIR			
1990 ASTM	5x1015	5x1014	
1991 Hwang#			1.5x1015*
2005 Porrini#		1x1015	1x1015*
2005 Inoue	1x1014		
2011 Zakel		2x1014	
2017 Inoue		1x1013	1x1014