Research

Short Communication: Optical Properties of Intrinsic Silicon at 300 K

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An updated tabulation is presented of the optical properties of intrinsic silicon relevant to solar cell calculations. The absorption coefficient, refractive index and extinction coefficient at 300 K are tabulated over the 0.25–1.45 μm wavelength range at 0.01 μm intervals.

Accurate tabulations of the optical properties of silicon are of use in standardizing calculations of silicon solar cell properties and in extracting other cell parameters from experimental measurements.

Recent measurements at both the ultraviolet[1,2] and infrared[3] ends of the spectrum have considerably improved the accuracy of silicon optical data at these wavelengths, rendering past tabulations[4–6] and assessments[7] largely obsolete. An updated tabulation of the absorption coefficient, α, and the real and imaginary parts of the refractive index (n and k, respectively) is given in Table I. The extinction coefficient is related to the absorption coefficient via the relationship $\alpha = 4\pi k/\lambda$, where λ is the free space wavelength. Data are given at 300 K over the 0.25–1.45 μm wavelength range at 0.01 μm intervals.

The real refractive index (n) values to 0.8 μm wavelength are based on recent ellipsometric measurements, nominally at 22°C.[1] Extinction coefficients to 0.46 μm wavelength are deduced from the same measurements. In both cases, small corrections to convert to 300 K were based on temperature dependencies reported for both higher[2] and lower[8] temperatures. Absorption coefficients were extracted from the extinction coefficient to 0.46 μm wavelength using the relationship given earlier. Beyond this wavelength, published absorption coefficient data[3,9,10] are considered more accurate and the reverse procedure was used.

From 0.46 to 1.0 μm, absorption coefficient data based on transmission measurements[9] of samples in the 5.5–249 μm thickness range were used, with a small correction to convert from the measurement temperature of 26°C. From 1.0 to 1.2 μm, similar measurements upon specimens in the 0.03–1.77 cm thickness range[10] form the basis of the data, again with temperature correction from the measurement temperature of 291 K. Beyond 1.2 μm wavelength, recent absorption coefficient values deduced from sensitive spectral response measurements[3] upon high-performance silicon cells are used.

At wavelengths beyond 1.0 μm wavelength, real refractive index data were deduced by a critical examination of past literature.[11–14] The more recent data[12–14] were consistent in that they all gave indices about 0.001–0.002 lower than the earlier data,[11] possibly owing to the use of purer silicon.[14] When corrected to 300 K, the refractive index at wavelengths longer than 1 μm could be described very accurately by the following expression, deduced from the discussion given by Moss *et al*,[15]

$$n^2 = 1 + \lambda^2/(0.0938\lambda^2 - 0.00866) \quad (1)$$

where λ is in μm. This was used to generate the data of Table I at wavelengths longer than 1 μm.

When extrapolated to short wavelengths, this expression gives values about 0.015 lower than the ellipsometric data[1] at wavelengths near 0.8 μm, just within the lower error bound of the latter data.[1]

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Table I. Optical properties of intrinsic silicon at 300 K. Data tabulated are the absorption coefficient (α), the real part (n) of the refractive index and the negative of the imaginary part (k, the extinction coefficient) for the wavelength range 0.25–1.45 μm.

λ(μm)	α(cm^{-1})	n	k	λ(μm)	α(cm^{-1})	n	k
0.25	1.84×10^{6}	1.694	3.666	0.70	1.90×10^{3}	3.774	0.011
0.26	1.97×10^{6}	1.800	4.072	0.71	1.77×10^{3}	3.762	0.011
0.27	2.18×10^{6}	2.129	4.690	0.72	1.66×10^{3}	3.751	0.010
0.28	2.36×10^{6}	3.052	5.258	0.73	1.54×10^{3}	3.741	0.009
0.29	2.24×10^{6}	4.426	5.160	0.74	1.42×10^{3}	3.732	0.008
0.30	1.73×10^{6}	5.055	4.128	0.75	1.30×10^{3}	3.723	0.008
0.31	1.44×10^{6}	5.074	3.559	0.76	1.19×10^{3}	3.714	0.007
0.32	1.28×10^{6}	5.102	3.269	0.77	1.10×10^{3}	3.705	0.007
0.33	1.17×10^{6}	5.179	3.085	0.78	1.01×10^{3}	3.696	0.006
0.34	1.09×10^{6}	5.293	2.951	0.79	9.28×10^{2}	3.688	0.006
0.35	1.04×10^{6}	5.483	2.904	0.80	8.50×10^{2}	3.681	0.005
0.36	1.02×10^{6}	6.014	2.912	0.81	7.75×10^{2}	3.674	0.005
0.37	6.97×10^{5}	6.863	2.051	0.82	7.07×10^{2}	3.668	0.005
0.38	2.93×10^{5}	6.548	0.885	0.83	6.47×10^{2}	3.662	0.004
0.39	1.50×10^{5}	5.976	0.465	0.84	5.91×10^{2}	3.656	0.004
0.40	9.52×10^{4}	5.587	0.303	0.85	5.35×10^{2}	3.650	0.004
0.41	6.74×10^{4}	5.305	0.220	0.86	4.80×10^{2}	3.644	0.003
0.42	5.00×10^{4}	5.091	0.167	0.87	4.32×10^{2}	3.638	0.003
0.43	3.92×10^{4}	4.925	0.134	0.88	3.83×10^{2}	3.632	0.003
0.44	3.11×10^{4}	4.793	0.109	0.89	3.43×10^{2}	3.626	0.002
0.45	2.55×10^{4}	4.676	0.091	0.90	3.06×10^{2}	3.620	0.002
0.46	2.10×10^{4}	4.577	0.077	0.91	2.72×10^{2}	3.614	0.002
0.47	1.72×10^{4}	4.491	0.064	0.92	2.40×10^{2}	3.608	0.002
0.48	1.48×10^{4}	4.416	0.057	0.93	2.10×10^{2}	3.602	0.002
0.49	1.27×10^{4}	4.348	0.050	0.94	1.83×10^{2}	3.597	0.001
0.50	1.11×10^{4}	4.293	0.045	0.95	1.57×10^{2}	3.592	0.001
0.51	9.70×10^{3}	4.239	0.039	0.96	1.34×10^{2}	3.587	0.001
0.52	8.80×10^{3}	4.192	0.036	0.97	1.14×10^{2}	3.582	0.001
0.53	7.85×10^{3}	4.150	0.033	0.98	9.59×10	3.578	0.001
0.54	7.05×10^{3}	4.110	0.030	0.99	7.92×10	3.574	0.001
0.55	6.39×10^{3}	4.077	0.028	1.00	6.40×10	3.570	0.001
0.56	5.78×10^{3}	4.044	0.026	1.01	5.11×10	3.566	–
0.57	5.32×10^{3}	4.015	0.024	1.02	3.99×10	3.563	–
0.58	4.88×10^{3}	3.986	0.023	1.03	3.02×10	3.560	–
0.59	4.49×10^{3}	3.962	0.021	1.04	2.26×10	3.557	–
0.60	4.14×10^{3}	3.939	0.020	1.05	1.63×10	3.554	–
0.61	3.81×10^{3}	3.916	0.018	1.06	1.11×10	3.551	–
0.62	3.52×10^{3}	3.895	0.017	1.07	8.0	3.548	–
0.63	3.27×10^{3}	3.879	0.016	1.08	6.2	3.546	–
0.64	3.04×10^{3}	3.861	0.015	1.09	4.7	3.544	–
0.65	2.81×10^{3}	3.844	0.015	1.10	3.5	3.541	–
0.66	2.58×10^{3}	3.830	0.014	1.11	2.7	3.539	–
0.67	2.38×10^{3}	3.815	0.013	1.12	2.0	3.537	–
0.68	2.21×10^{3}	3.800	0.012	1.13	1.5	3.534	–
0.69	2.05×10^{3}	3.787	0.011	1.14	1.0	3.532	–

Table I—(*continued*)

$\lambda(\mu m)$	$\alpha(cm^{-1})$	n	k	$\lambda(\mu m)$	$\alpha(cm^{-1})$	n	k
1.15	6.8×10^{-1}	3.530	–	1.30	4.5×10^{-5}	3.504	–
1.16	4.2×10^{-1}	3.528	–	1.31	2.7×10^{-5}	3.503	–
1.17	2.2×10^{-1}	3.526	–	1.32	1.6×10^{-5}	3.501	–
1.18	6.5×10^{-2}	3.524	–	1.33	8.0×10^{-6}	3.500	–
1.19	3.6×10^{-2}	3.522	–	1.34	3.5×10^{-6}	3.498	–
1.20	2.2×10^{-2}	3.520	–	1.35	1.7×10^{-6}	3.497	–
1.21	1.3×10^{-2}	3.528	–	1.36	1.0×10^{-6}	3.496	–
1.22	8.2×10^{-3}	3.516	–	1.37	6.7×10^{-7}	3.495	–
1.23	4.7×10^{-3}	3.515	–	1.38	4.5×10^{-7}	3.493	–
1.24	2.4×10^{-3}	3.513	–	1.39	2.5×10^{-7}	3.492	–
1.25	1.0×10^{-3}	3.511	–	1.40	2.0×10^{-7}	3.491	–
1.26	3.6×10^{-4}	3.510	–	1.41	1.5×10^{-7}	3.490	–
1.27	2.0×10^{-4}	3.508	–	1.42	8.5×10^{-8}	3.489	–
1.28	1.2×10^{-4}	3.507	–	1.43	7.7×10^{-8}	3.488	–
1.29	7.1×10^{-5}	3.506	–	1.44	4.2×10^{-8}	3.487	–
				1.45	3.2×10^{-8}	3.486	–

Over the wavelength range of 0.8–1.0 μm, where there appeared to be no consistent experimental data of comparable accuracy, the data sets were merged using a wavelength-dependent weighting.

The error limits on the tabulated extinction and absorption coefficient data are estimated to increase from ±0.3% at 0.25 μm wavelength[1] to ±4% beyond 0.46 μm, ±10% beyond 1.2 μm and even larger beyond 1.4 μm wavelength. For the real part of the refractive index, the estimated accuracy is better than ±0.1% beyond 1.0 μm, increasing to about ±0.5% at shorter wavelengths, except below 0.3 μm where it increases to ±1%.

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