Stark parameters of some asymmetrical Si II lines

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Abstract. Six lines of SiII are experimentally studied in pulsed plasma generated by Nd:Yag laser breakdown on pure solid silicon target. A set of experimental Stark parameters of asymmetrical lines are measured in temperature range from 14 000 K to 18 000 K (using Boltzmann plot). Calculated values of the electron density (using Griem’s formula) vary from 1.7 to 6.1 x10^23 m^-3. Processed spectral lines are 333.982 nm (3s^2 4p - 3s^2 6s) and 397.746 nm, 399.177 nm, 399.801 nm, 401.622 nm (3d' 2F0 - 4f' 4G) and (3d' 2F0 - 4f' 2G) of astrophysical interest. Asymmetrical line shapes are synthesized by a sum of two semi-Lorentzian distributions. The obtained fit is in good agreement with the measured spectra.

1. Introduction
Stark parameters values of silicon lines are needed [1, 2] for the knowledge of the atmosphere physical conditions in low temperature silicon stars at temperature from 10 000 to 20 000 K. Various theories [3-10] provide calculated values of symmetrical lines of Lorentzian shape. But the presented profiles are not. That is a characteristic which has been studied before [11-15] but in the present case, up to now, there is no evident explanation.

Under the experimental conditions, almost all observed lines are of asymmetrical shape and four lines belonging to the (3d' 2F0 - 4f' 4G) and (3d' 2F0 - 4f' 2G) multiplets are studied for the first time.

2. Experimental set up
The data acquisition was performed [16] by mean of Nd:Yag laser breakdown on solid silicon (10ns pulse width, 300 mJ energy). The silicon sample of purity 99.999 % was a cylindrical rod of 5 mm in diameter and 50 mm in length. The sample, placed in the vacuum cell, was fixed to a helicoidally displacement device built up with a threaded rod, driven by a step motor (Figure. 1).

![Figure 1: Helicoidally displacement device and breakdown cell: 1 - laser beam. 2 – plasma. 3 – target. 4 - optical bundle.](image-url)
The rotation rate was set by a Hewlett Packard TTL pulses generator which frequency was set as a function of the repetition rate of the laser pulses. The laser beam was focused at regular intervals onto the surface of the cylindrical sample and the repeatability of the plasma controlled by observing the spectral intensity of the observed lines. A monochromator TRIAX 180 from Jobin-Yvon with a 2400 grooves per mm grating (blaze: 330nm and slit 25 µm) was coupled to an UV-visible 1024×256 ICCD camera from Jobin-Yvon. The resulting resolution was 30 pm per pixel. The bundle was built of 16 optical fibers of 200 µm, with a circular entrance aperture and a linear exit at the monochromator slit. The ICCD was intensified during 200 ns, the delay after the laser pulses was 125 ns and 295 ns for the plasma in vacuum and in Xenon, respectively. For a given set of parameters each spectrum was recorded in accumulative mode for 100 laser pulses, over the 256 lines of the ICCD. These measurements were repeated 20 times. Then, the plasma spectrum was calculated as the median of those 20 spectra.

The apparatus function was measured using Hg or Ar lamps and the thermal noise was measured at the beginning and at the end of each acquisition sequence. Few quantities of Xenon were added to determine the temperature, using Boltzmann plot of the Xe II lines. The accuracy of measured values is about 10 % due to the uncertainties induced by the spectrometric technique.

3 Reduction of the data
The unfolding procedure of Si II lines profiles was done using a Matlab program according to the algorithm described below: the two first steps constitute the spectra pretreatment and the following steps permit to calculate a modeled spectrum which is the sum of synthetic background and synthetic lines. For each studied multiplet, these contributions are depending on parameters which are optimized by the Simplex method in order to minimize the quadratic error between the real and modeled spectrum.

1. Once the wavelength calibration is performed, the program used all thermal noise files of the ICCD to calculate the median noise.
2. Then, it proceeded to the listing of all the files of the real spectra to classify them by laser beam incident energy (and therefore by plasma temperature). The adopted spectrum, for each laser energy, was the median spectrum from which the median noise spectrum must be subtracted.
3. The synthetic background is a second-degree polynomial whose coefficients are estimated from the real one. These coefficients are thereafter optimized using the Simplex method.
4. A synthetic line is made using a contribution of two semi-Lorentzian distributions : the left half profile is characterized by the half-width $\gamma_1$ and the half right profile has an half-width $\gamma_2$. This profile model successfully reproduced the observable data (best fit of the real spectrum) and has not yet theoretical justification. The half-widths of synthetic lines are optimized by the Simplex method.
5. The final synthetic spectrum is the sum of each synthetic line convoluted by the measured apparatus function added to the synthetic background.

4. Results
Series of very stable and repeatable spectra of singly ionized silicon were obtained for electron density and temperatures ranges: \( N_e = 1.70 \cdot 6.10^{21} \) m\(^{-3} \); \( T=14,000 \) K to 18,000 K.
A check for a temperature gradient along the radius of the discharge using an Abel inversion did not detect any in-homogeneity which can be, eventually, responsible of the asymmetry and no self-absorption was detected. It was noticed that the line at 399.177 nm belonging to the same multiplet was of symmetrical shape for all the temperature ranges. Due to the asymmetric shape of most of the SiII profiles the Griem’s formula was used to measure the electron density, instead of the SiII line width.
Figures 2 and 3 report observed lines in a large range of wavelength where we note, particularly, the faint lines resulting from the transitions \((3d^2\text{F}^0, 4f^+\text{G})\) and \((3d^2\text{F}^0, 4f^-\text{G})\). Figure.4 reports the real and synthesized spectra of the doublet \((3s^2\text{p}^6 \cdot 3s^2\text{6s})\) and those of the faint lines \((3d^2\text{F}^0, 4f^+\text{G})\) and \((3d^2\text{F}^0, 4f^-\text{G})\) are reported in the figure 5. In spite of their low intensity, they are recorded without saturation of the detector. For all multiplets, the smooth and continuous line indicates the modeled spectrum.
Table: Measured values of Stark parameters

| Temperature (°K) | λ₀ (nm) | λₘ (nm) | Δλ (nm) | I_max (r.u) | γ₁ (nm) | γ₂ (nm) |
|-----------------|---------|---------|---------|-------------|---------|---------|
| 14000           |         |         |         |             |         |         |
| T= 14000 °K     | 333.314 | 333.313 | 0.001   | 1110.85     | 0.166   | 0.650   |
|                 | 333.314 | 333.339 | 0.025   | 1330.21     | 0.210   | 0.590   |
|                 | 333.314 | 333.334 | 0.020   | 1258.51     | 0.203   | 0.749   |
|                 | 333.314 | 333.429 | 0.115   | 1247.80     | 0.480   | 0.556   |
|                 | 333.314 | 333.429 | 0.115   | 1247.80     | 0.480   | 0.556   |
|                 | 333.982 | 333.926 | 0.056   | 2186.86     | 0.905   | 0.443   |
|                 | 397.746 | 397.766 | 0.200   | 968.62      | 0.365   | 0.443   |
|                 | 399.177 | 399.181 | 0.004   | 2490.60     | 0.310   | 0.310   |
|                 | 399.801 | 399.799 | 0.002   | 1498.47     | 0.252   | 0.348   |
|                 | 401.622 | 401.562 | 0.060   | 901.17      | 0.195   | 0.426   |

Measured values (with a precision of about 10%) of left (γ₁) and right (γ₂) half-widths of 6 spectral lines, as well the Stark shifts, for 5 values of the temperature are reported in table 1. The first column indicates the central wavelengths according to Striganov and Sventitskii [18]. They correspond, in a more satisfactory way, to the observable values than those brought back from the NIST [19] which, moreover, even mention the spectral characteristics of the transitions (3d⁺²F⁰⁻⁴f⁺⁴G) and (3d⁺²F⁰⁻⁴f⁻⁴G) (neither energy levels, neither spectral terms, nor statistical weights etc...) The second column brings back the wavelengths of maximum observed for the transitions considered, while Δλ indicates the Stark shift calculated by subtraction between the values of the first and the second columns.
Fig. 2: Observed lines of the doublet 3s^24p - 3s^26s in large range of wavelength

Fig. 3: Observed lines of 3d'2F_0 - 4f'4G and 3d'2F_0 - 4f'2G transitions in large range of wavelength

Fig. 4: Real and synthesized spectra of the doublet 3s^24p - 3s^26s

Fig. 5: Real and synthesized spectra of the doublets 3d'3F_1 - 4f'4G and 3d'3F_1 - 4f'2G

The intensities of the lines are reported in columns 4 and 5 while $\gamma_1$ and $\gamma_2$ are the two half-widths of the lines according to the above mentioned method of calculation. The numerical values of the half-widths at half maximum indicate that lines are asymmetrical except the line 399.177 nm which is symmetrical for all the values of temperature and the line 401.622 nm asymmetric for $T=18000^\circ$K only. The Stark shift is very weak for the line 399.177 nm. To our knowledge asymmetry for the presented transitions, neither experimental nor theoretical, has been, up to now, reported.

References
[1] Lanz T and Artru M C 1985 Physica Scripta 32 115
[2] Lesage A and Redon R 2004 A&A 478 765
[3] Griem H R 1968 Phys. Rev 165 258
[4] Griem H R 1974 Spectral line broadening by plasmas (New York, Academic press)
[5] Sahal-Brechot S 1969a A&A 1 91
[6] Sahal-Brechot S 1969b A&A 2,322
[7] Lanz T Dimitrievic M S and Artru M C 1988 A&A 192 249
[8] Ralchenko Yu V Griem H R and Igor Bray 2003 JQSRT 81 371
[9] Ralchenko Yu V Griem H R Igor Bray and Dimitri V Pura 1999 Phys. Review A 59 3
[10] Alexiou S 1997 in 13th Int. Conf. on Spectral Line Shapes, ed. M Zoppi and L Ulivi
[11] Ciurylo R Physical Review A 58, Issue 2, pp. 1029-1039
[12] Torres J Palmarés J M Gigolos M A Gameiro A Sola A and Van der Mullen J J 2008 Spectrochimica Acta Part B: Atomic Spectroscopy 63 (9) 939
[13] Nikolic D. Djurovic S Mijatovic Z Kobilarov R Vujicic B and Irian M 2004 JQSRT 86 (3) 285
[14] Günter S and Könies A 1994 JQSRT 52 (6) 819
[15] Szudy J and Baylis W E 1977 JQSRT 17 (5) 681
[16] Matheron P Escarguel A Redon R Lesage A and Richou J 2001 JQSRT 69 535
[17] Deron C Perrin M-Y and Soufiani A. 2005, in 6th World Conference on Experimental Heat Transfer, Fluid Mechanics and Thermodynamics Matsushima Miyagi Japan
[18] Striganov A R and Sventitskii N S 1968, in Tables of Spectral lines of Neutral and Ionized Atoms IFI/Plenum
[19] Ralchenko Yu Kramida A E Reader J and NIST ASD Team 2008 NIST Atomic Spectra Database (version 3.1.4) [Online] National Institute of Standards and Technology Gaithersburg MD