

Microscale Spatially Resolved Characterization of Highly Doped Regions in Laser-Fired Contacts for High-Efficiency Crystalline Si Solar Cells

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Microscale Spatially Resolved Characterization of Highly Doped Regions in Laser-Fired Contacts for High-Efficiency Crystalline Si Solar Cells

A. Roigé, J. Alvarez, J.-P. Kleider, I. Martín, R. Alcubilla, and L. F. Vega

5 Abstract—Laser-fired contact (LFC) processes have emerged as a promising approach to create rear local electric contacts in p-type 6 crystalline silicon solar cells. Despite this approach has been suc-7 8 cessfully applied in devices showing efficiencies above 20%, there is still a lack of knowledge about some specific features of LFCs 9 10 at the submicron level. In this study, we used micro-Raman and 11 microphotoluminescence (PL) spectroscopies to carry out a highresolution spatially resolved characterization of LFCs processed 12 in Al2 O3 - passivated c-Si wafers. Relevant information concerning 13 features such as local doping distribution and crystalline fraction 14 of the laser-processed region has been obtained. In particular, in-15 teresting qualitative and quantitative variations concerning the 16 doping profile have been observed between LFCs processed at dif-17 ferent laser powers. Finally, conductive-atomic force microscopy 18 19 measurements have allowed to identify the existence of highly con-20 ductive zones inside the LFCs greatly correlated with highly doped 21 regions revealed by Raman and PL data. This study gives a detailed 22 insight about the LFCs characteristics at the submicron level and 23 their possible influence on the performance of final devices.

Index Terms—Crystalline silicon, laser-fired contacts (LFCs),
 microphotoluminescence spectroscopy, micro-Raman spec troscopy.

I. INTRODUCTION

F ROM an industrial point of view, one of the most interesting crystalline silicon (c-Si) solar cell technologies to obtain high-efficiency devices is the passivated emitter and rear cell concept. Recently, the industrial implementation of this cell type has been significantly simplified by using the so-called laser fired contact (LFC) approach for the creation of the back contacts of the cell [1], [2]. This method is based on firing the

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rear Al metallization layer by a laser beam in order to create electrical point contacts between the Al layer and the silicon substrate through the passivation layer.

A key feature for the good operation of LFCs is the formation of an Al-doped p+ region under the contacted surface area. This is achieved by the diffusion of Al atoms from the predeposited Al layer into the molten Si. This p+ region not only creates a local back-surface field that induces a relatively low recombination velocity below the contacts, but also ensures a low-contact resistance.

LFC approach can be applied by using any of the dielectric layers that have demonstrated excellent c-Si passivating properties such as silicon oxide (SiO_2) [3], silicon nitride (SiN_r) [4], amorphous-silicon carbide $(a-SiC_x)$ [5], and most recently, aluminum oxide (Al₂O₃) [6]. In the case of using the latter passivating material, an interesting alternative to the conventional LFC process can be applied. In this case, the Al_2O_3 layer it-51 self can be used as Al-dopant source for the formation of the 52 p+ region, and hence, the LFC can be done directly onto the 53 Al₂O₃/c-Si, instead of being done onto the Al/dielectric/c-Si 54 stack. This approach enables a lower laser power operation in 55 comparison with conventional LFC process where higher laser 56 powers are needed to fire the aluminum through the dielectric 57 layer. These type of LFC processes have been already used to 58 fabricate solar cells showing efficiencies well above 20% [6]. 59

Despite the evident success in the implementation of the LFC 60 approach in real devices, there is still a lack of information about 61 specific features of LFCs such as the doping profile of the p+ 62 region, the level of induced-stress, and/or the structural prop-63 erties of the laser-processed region. The most likely reason for 64 that is the difficulty to find experimental techniques that match 65 a high-lateral resolution (below 10 μ m) and sensitivity to the 66 parameters wanted to be studied. Recently, a study of LFC cross 67 sections [7] have demonstrated that Raman and photolumines-68 cence (PL) spectroscopies in microconfiguration are techniques 69 that fulfill the mentioned requirements. 70

In this study, we have carried out high-resolution micro-71 Raman and micro-PL spectroscopy measurements on different 72 LFCs processed in Al₂O₃-passivated c-Si samples. Thanks to 73 the high lateral resolution down to 1 μ m achieved in our ex-74 periments, we have been able to perform a detailed study of 75 relevant LFC properties such as the doping profile, induced-76 stress, and crystallinity fraction, giving an important insight 77 about the LFC formation. Three LFCs processed at different 78 incident laser power have been studied in order to analyze the 79 influence of the laser power on the studied features. Finally, in 80

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order to complement the PL and Raman data, conductive-atomic
 force microscopy (c-AFM) measurements have been performed
 in order to study local resistance variations inside the LFCs.

It is worth to mention that the term LFC has been used since more than a decade to describe the firing of the predeposited aluminum through a dielectric layer. Despite the process used here is fundamentally different, its finality and application in solar cell devices is the same. For simplicity, we have maintained the term LFC to refer to our laser-processed locally doped regions.

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II. EXPERIMENTAL METHODS AND MATERIALS

Samples under study were based on 2.5 Ω ·cm boron-doped 91 float-zone (FZ) crystalline Si (c-Si) wafers with a thickness of 92 250 μ m and (1 0 0) crystal orientation. c-Si wafers were pas-93 sivated by a 25-nm-thick aluminum oxide (Al₂O₃) film which 94 95 was grown by thermal atomic layer deposition. Laser fired spots 96 were processed on the top of the Al₂O₃-passivated c-Si sam-97 ples creating small apertures in the alumina layer and melting a small part of the underlying c-Si subsurface region. LFCs were 98 processed by a 1064 nm Nd:YAG lamp-pumped laser working 99 at 100 ns of pulse duration. Each contact is a consequence of 100 six pulses at a repetition rate of 4 kHz. Three different LFCs 101 processed with a laser power of 0.98, 1.1, and 1.43 W were 102 studied, corresponding to pulse energies of 245, 275, and 357.5 103 μ J. The laser beam shows a Gaussian profile with a beam waist 104 characterized by a radius of 70 μ m at the focus plane where all 105 the samples were processed. After laser processing and prior to 106 carry out the measurements, samples were immersed in an HF 107 1% solution bath during 40 s (or until obtaining an hydrophobic 108 silicon surface) in order to remove the Al₂O₃ layer. Addition-109 ally, three boron-doped FZ c-Si wafers with doping densities 110 of 1×10^{15} , 5×10^{18} , and 1×10^{20} cm⁻³ were used in order to 111 obtain reference Raman and PL spectra. 112

Micro-Raman and microphotoluminescence experiments 113 were carried out with a WITEC alpha300. A diagram of the 114 Witec equipment setup can be found in [8]. A diode-pumped 115 laser with a wavelength of 532 nm was used as an excitation 116 source resulting in a penetration depth of about 1 μ m. Micro-117 Raman and micro-PL measurements were performed with a 100 118 VIS (visible), NA (numerical aperture) = 0.9 and a $20 \times IR$ Х 119 (Infrared), NA = 0.45, respectively. The resulting beam spot 120 size on the sample surface is in diameter below 1 and 2 μm for 121 Raman and PL measurements, respectively. Raman scattering 122 signal was recorded through a 300-mm imaging spectrometer 123 equipped with both a 600 lines/mm and 1800 lines/mm grat-124 ing, and a 1024×127 CCD (charge-coupled device) camera 125 visible-optimized, whereas PL signal was collected through an 126 additional 300-mm spectrometer composed of two gratings (150 127 and 300 lines/mm) and a 1024×1 pixel linear InGaAs photodi-128 ode array optimized for spectroscopy applications in the range 129 1–1.7 μ m. It is worth to mention that the incoming laser power 130 on the sample surface for the Raman measurements was kept 131 below 3 mW. With our configuration, 3 mW was measured to 132 be the pumping limit to keep the photo-generated carrier den-133 sity below threshold and, therefore, to avoid Fano resonances 134 induced by high injection conditions [15]. 135

Local electrical measurements through the c-AFM technique 136 were performed using a Digital Instruments Nanoscope IIIa 137 Multimode AFM associated with the home-made conducting 138 probe extension called "Resiscope" [9]. This extension allows 139 us to apply a stable dc bias voltage (from -10 to +10 V) to the 140 sample and to measure the resulting current flowing through the 141 tip as the sample surface is scanned in contact mode, yielding a 142 local resistance map covering resistance values in the range 10^2 – 143 $10^{12} \Omega$. Current–Voltage (*I–V*) measurements are also permitted 144 with this extension. Highly boron doped diamond-coated Si 145 AFM cantilevers, with an intermediate spring constant of about 146 3 N/m, proved to be the most suitable AFM tips for making 147 electrical measurements on LFCs. Due to the AFM tip radius 148 $(\sim 50 \text{ nm})$, c-AFM measurements offer a much greater lateral 149 resolution. This latter depends on the electrical contact radius 150 between the tip and the surface. In the particular case of flat 151 surfaces, the electrical contact radius can be much smaller than 152 AFM tip radius. The probed depth remains in the nanoscale 153 range, but it is linked, among other parameters, to the applied 154 voltage and the local electrical transport properties. 155

III. RESULTS AND DISCUSSION 156

A. Doping Characterization by Micro-Raman Spectroscopy 157

Doping profiles in c-Si can be monitored by studying both 158 the Full Width at Half Maximum (FWHM) [10] and the Fano 159 resonance [11] of the first-order Si Raman peak. In particular, 160 Fano resonances are evident in the Si Raman spectra at hole 161 concentrations above 10^{18} cm⁻³ by a characteristic asymmetry 162 in the first-order Si Raman line. This asymmetry results from 163 the resonant interaction between discrete phonon states and a 164 continuum of hole states [12], [13]. The Raman peak line shape 165 can be described by the following expression [11]: 166

$$I(k) = I_0 \cdot \frac{[q + 2(k - k_{ph})/\Gamma]^2}{1 + [2(k - k_{ph})/\Gamma]^2}$$
(1)

where I_0 is a scaling factor, k_{ph} is the frequency associated to 167 the Raman peak maximum, Γ corresponds to the FWHM, and q168 is the asymmetry parameter, which is correlated with the doping 169 level of the sample being studied. The lower the q parameter, 170 the higher the doping level. The first-order Si Raman peak can 171 be also influenced by stress and/or by the material crystalline 172 fraction. The former can be monitored by the peak frequency 173 shift, whereas the latter is evidenced by a peak broadening from 174 the c-Si to the amorphous-Si state. 175

Fig. 1 shows the optical microscope images (left-hand side) 176 and the corresponding Raman peak width maps (right-hand side) 177 of the three LFCs under study processed at 0.98 (a) and (b), 178 1.1 (c) and (d), and 1.43 W (e) and (f). Maps were obtained 179 from the raw Raman peak width, not from the fitted Γ . The 180 corresponding LFC diameters were 43.8, 54.5, and 74.2 μ m, 181 respectively. For ensuring a good observation of the obtained 182 data, the microscope images and the Raman maps of the three 183 contacts have been represented with a slightly different scale. In 184 addition for clarity, the physical dimensions of the LFCs have 185 been represented in Raman maps by a green dotted circle. As 186 explained previously, the width of the first-order Raman peak 187

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Fig. 1. Optical microscope images (left-hand side) and Raman peak width maps (right-hand side) of the three LFCs under study processed at 0.98 (a) and (b), 1.1 (c) and (d), and 1.43 W (e) and (f). Brighter zones in the Raman peak width maps correspond to zones with higher doping density.

can be used to monitor the doping level of the sample under 188 study. Hence, the zones that evidence an increase of the Raman 189 peak width in Fig. 1 (brighter zones) are qualitatively correlated 190 with zones with a higher doping level. The LFC processed at 191 0.98 W evidences slightly higher levels of doping at the central 192 part of the contact. In contrast, the contact processed at 1.1 W 193 194 [see Fig. 1(d)] evidences a brighter concentric corona pointing out a wider Raman peak and consequently an increase of the 195 doping level. Following the same trend, for the contact processed 196 using the higher laser power [see Fig. 1(f)], the border of the 197 contact is the area that evidences a higher level of doping. The 198 different Raman maps illustrated in Fig. 1 demonstrate that 199 the laser power plays an important role on the distribution of 200 201 the highly doped regions inside the contacts. More precisely, it seems that for higher laser powers, the highly doped regions 202 move toward the border of the contact. Two-dimensional depth 203 profiling across LFCs (maps not shown for space limitations) 204 revealed the same results. This fact corroborates that the features 205 of Raman maps shown in Fig. 1 were not affected by variations 206 in surface topography of LFCs. 207

The correlation between the Raman peak widening observed 208 in Fig. 1 and the expected increase in the doping density is con-209 firmed by data shown in Fig. 2. This figure shows the averaged 210 Raman spectra corresponding to the zones with higher doping 211 of images b, d, and f of Fig. 1. In particular, the averaged spectra 212 were calculated from the yellow-colored areas of Raman maps. 213 An averaged spectrum corresponding to an unprocessed area 214 (outer region of LFC) is also shown (yellow dashed line). In 215



Fig. 2. Averaged Raman spectra corresponding to the brighter zones of maps b, d, and f of Fig. 1. For comparison, an averaged Raman spectra corresponding to an unprocessed surface area has been also represented (yellow dashed line). The inset shows the Raman spectra recorded from the three reference c-Si wafers with different doping level.



Fig. 3. Raman spectra obtained at specific points inside LFCs processed at 1.1 W (r1, r2) and 1.43 W (r3). In addition to the first-order Raman peak, a second peak characteristic of microcrystalline silicon sets in at lower wavenumbers. For comparison, a Raman peak related to an unprocessed area (outer region of LFCs) is also depicted.

order to facilitate the observation of Fano resonances, Raman 216 spectra have been represented using a semilog scale. As it can 217 be observed, the Fano resonance is clearly identified for all Ra-218 man spectra except for the one obtained out of the LFC, which 219 shows a symmetric Raman line shape. This qualitatively con-220 firms that the brighter zones in maps of Fig. 1 are correlated 221 with areas with a higher doping level. The increase in doping 222 is also greatly confirmed by the inset, where the Raman spectra 223 recorded from three reference c-Si wafers with doping levels of 224 1×10^{15} , 5×10^{18} , and 1×10^{20} cm⁻³ clearly evidence the 225 same trend concerning the Fano resonance. Another important 226 feature observed in the main plot of Fig. 2 is that the LFCs 227 processed with a higher laser power have associated a higher 228 Fano asymmetry. Hence, the use of higher laser powers results 229 in LFCs with higher doping densities. 230

In order to get further important information about the LFCs 231 formation, we depict in Fig. 3 the Raman spectra recorded 232 at three specific points (r1, r2, and r3) inside two LFCs pro-233 cessed at 1.1 W (r1, r2) and 1.43 W (r3) (contact images and 234 point positions not shown). A fourth Raman spectrum corre-235 sponding to a nonprocessed surface area is also represented 236 as a reference. As it can be observed, in addition to the first-237 order c-Si Raman line positioned at 520.9 cm⁻¹, new Raman 238 bands can be identified at lower wavenumbers in the range be-239 tween 500 and 515 cm^{-1} . These latter bands are commonly as-240 signed to microcrystalline silicon [16], [17]. Indeed, the Raman 241



Fig. 4. Fitting using (2) of the Raman spectrum corresponding to the highlydoped region of the LFC processed at 1.1 W. Fit gave a q parameter of 59 which is correlated to a doping level of about 5.8×10^{18} cm⁻³.

spectra of microcrystalline-Si are currently decomposed into 242 three bands: crystalline (\sim 520 cm⁻¹), intermediate band (500– 243 515 cm⁻¹, usually interpreted as a signature of the grain bound-244 aries or small crystallites grain size <10 nm), and amorphous 245 $(480 \,\mathrm{cm}^{-1})$. The following decomposition is used to quantify the 246 crystalline fraction [18]. The observation of these new Raman 247 bands at specific points inside the LFCs suggests that molten Si 248 material fraction solidifies in a structure involving crystallites, 249 grain boundaries, and an amorphous phase, at least in specific 250 zones inside the contacts. However, the crystalline fraction in 251 these zones reveals to be high indicating a negligible amorphous 252 component. 253

The contribution of microcrystalline-Si components to the obtained Raman spectra is further confirmed by the fact that all Raman spectra recorded inside the LFCs could be significantly better fitted using a rewriting of (1) that considers a second Lorentzian function related to the contribution of the microcrystalline Si formation. In fact, the expression that has been used to fit the Raman data is the following:

$$I(k) = I_0 \cdot \frac{[q + 2(k - k_{ph})/\Gamma]^2}{1 + [2(k - k_{ph})/\Gamma]^2} + \frac{A}{1 + [2(k - k_m)/\Gamma_m]^2}$$
(2)

where A corresponds to the intensity, k_m is the frequency of 261 the peak maximum, and Γ_m is the peak width of the Raman 262 band related to the microcrystalline-like component. It is worth 263 to mention that the position of the second Lorentzian function 264 was limited to values between 505 and 517 cm^{-1} . As observed 265 in Fig. 4 for a LFC processed at 1.1 W, the fit using (2) shows 266 very good adjustment paving the way to obtain a reliable quan-267 tification about the doping level inside the LFCs. 268

Table I shows the q asymmetry parameters resulting from 269 the best fit of (2) to the Raman spectra related to the highly 270 doped regions of the three LFCs under study. Data were calcu-271 lated from at least two LFCs for each one of the three values of 272 laser power. The obtained q parameters clearly illustrate that the 273 higher the laser power, the higher the doping density. According 274 to the calibration tables reported in [10] and [11], we have ob-275 tained maximum doping levels in the range of $1.17-3.83 \times 10^{18}$, 276 $4.58-6.06 \times 10^{18}$, and $2.15-5.02 \times 10^{19}$ cm⁻³ for the LFCs pro-277 cessed at 0.98, 1.1, and 1.43 W, respectively. It is important to 278

TABLE I q Asymmetry Parameter Obtained From the Fitting of (2) to the Averaged Raman Spectra Related to the Highly Doped Regions of the Three LFCs Under Study.

power (W)	q (arb.units)	doping ref. [10] $(\times 10^{18} \text{ cm}^{-3})$	doping ref. [11] $(\times 10^{18} \text{ cm}^{-3})$
0.98	90 ±7	3.13 - 3.83	1.17 – 2.35
1.10	61 ± 4	5.19 - 6.06	4.58 - 6.03
1.43	16 ± 2	21.49 - 27.93	42.19 - 50.17

The corresponding doping densities were calculated using the calibration tables reported in [10] and [11].



Fig. 5. (a) Raman spectra center of mass map of a LFC processed at 1.43 W. (b) Specific Raman spectra associated with points s1, s2, and s3 are also plotted.

remark that the intensity of the second Lorentzian peak related to the multicrystalline component was observed to increase with higher laser powers. This suggests that the use of higher laser powers decreases the crystalline fraction of the solidified Si volume. 283

Fig. 5(a) shows the Raman spectra center of mass map of a 284 LFC processed at 1.43 W. The Raman spectra of the selected 285 points (s1, s2, and s3) are represented in Fig. 5(b). The center 286 of mass was calculated considering a frequency range between 287 480 and 560 cm^{-1} ; thus, as confirmed by Raman spectra of 288 Fig. 5(b), it could be qualitatively correlated with the frequency 289 shift of the first-order Si Raman peak. The first-order Raman 290 line of s1, s2, and s3 Raman spectra is centered at 520.8, 519.3, 291 and 518.7 $\rm cm^{-1}$, respectively. Notice that the center of mass 292 values represented by the color scale bar of Fig. 5(a) are shifted 293 toward higher frequencies respect the Raman peak position val-294 ues mentioned previously. This is induced by the contribution 295 of the Fano resonance which moves de center of mass toward 296 higher energies respect the peak maximum. As it can be seen, 297 the Raman peak position suffers a red shift of about 2 cm^{-1} at 298 the border of the contact. Interestingly, areas of the contact that 299 show such a red shift exactly match with areas of the 1.43 W 300 LFC that evidence higher levels of doping [see Fig. 1(f)]. It has 301 been reported, that Raman spectra obtained from samples with 302 doping levels above 5×10^{18} cm⁻³ not only exhibit the so-called 303 Fano resonance, but also show a red shift in the Raman peak 304 maximum [19]. The expected theoretical peak shift induced by 305 an increase in doping satisfies: 306

$$k = k_0 + \frac{\Delta\Gamma}{2\,q} \tag{3}$$



Fig. 6. PL center of mass maps of LFCs processed at (a) 0.98 W and (b) 1.43 W. The green dotted circles delimit the physical dimensions of the LFCs.

where k_0 is the peak position of the bulk un-doped and stress 307 free c-Si and $\Delta\Gamma$ is the change in the Raman peak width due 308 to doping. The expected theoretical peak shifts resulting from 309 (3) for a q parameter of 16 (see Table I) takes values of about 310 0.5 cm⁻¹. These theoretical values are significantly lower than 311 those observed in Fig. 5, i.e., about 2 cm^{-1} . This fact suggests 312 that in addition to the red shift induced by an increase of the 313 doping level, a second contribution in the Raman shift is also 314 present. We correlate this second contribution with stress pos-315 sibly induced by the laser process. LFCs processed at 0.98 and 316 1.1 W do not show any significant red shift in the first-order 317 Raman peak maximum. Thus, the level of laser power used to 318 process the LFCs probably plays an important role in the level 319 of stress induced by the laser process. 320

321 B. Doping Characterization by

322 Photoluminescence Spectroscopy

Band-to-band photoluminescence spectroscopy senses the ra-323 diative recombination between photo-generated electrons in the 324 conduction band (CB) and the corresponding holes in the va-325 lence band (VB). As an increase in doping density induces a 326 reduction of the energy gap between CB and VB, PL has been 327 proven as a reliable tool for monitoring the band-gap shift in 328 heavily doped c-Si [14]. In this sense, micro-PL spectroscopy 329 330 is also capable to characterize the high doping levels expected inside the LFCs. In fact, micro-PL has been applied to charac-331 terize the doping density in laser-induced highly doped regions 332 cross sections [7]. In our study, we study the position and line 333 shape of the PL emission line by monitoring the center of mass 334 of the PL spectra recorded inside the LFCs. 335

Fig. 6 shows the PL center of mass maps corresponding to 336 the LFCs processed at 0.98 (a) and 1.43 W (b). The averaged 337 PL spectra obtained from the brighter zones of the PL maps 338 are illustrated in Fig. 7. As it can be seen, the shift of the 339 PL spectra center of mass revealed by the color scale bars of 340 Fig. 6 is linked to an increase of the PL intensity at lower 341 energies. In particular, the PL spectrum related to the 0.98 W 342 LFC evidences a slight increase of the left PL spectrum shoulder, 343 whereas the PL spectrum related to the 1.43 W LFC shows a 344 significantly higher increase of the left PL spectrum shoulder 345 plus a blue shift in the PL emission maximum. We correlate 346 this shift of the PL line with a Si band-gap renormalization 347 induced by a strong increase of doping in the measured material 348 volume. The increase in the doping density is further confirmed 349 by the inset of Fig. 7 which illustrates the PL spectra recorded 350 from c-Si wafers with doping levels of 1×10^{15} , 5×10^{18} , and 351



Fig. 7. Averaged PL spectra corresponding to the highly doped regions (yellow-colored regions) of PL center of mass maps a (0.98 W) and b (1.43 W) illustrated in Fig. 6. Additionally, a PL spectra recorded out of the processed LFC regions is also represented. The inset plot shows the PL spectra corresponding to three reference c-Si wafers with different doping level.

 1×10^{20} cm⁻³. As it can be seen, the inset and the main plot 352 show the same trend. For all these reasons, we confirm that 353 the brighter zones of the PL maps of Fig. 6 have associated 354 a higher doping level. Interestingly, the two represented PL 355 maps greatly correlate with the homologous Raman width maps 356 of Fig. 1, demonstrating the successful application of micro-357 Raman and micro-PL techniques for studying doping-density 358 variations above 1×10^{18} cm⁻³ with submicron resolution. 359

C. Laser-Fired Contact Characterization by Conductive-Atomic Force Microscopy

Finally, the study of LFCs was completed by their character-362 ization by means of c-AFM measurements. The aim of these 363 studies is to analyze if the laser-processed material volume 364 shows preferential conductive zones, and if that is the case, 365 to study their correlation with the highly doped regions deduced 366 from Raman and PL data. C-AFM measurements have been di-367 vided in two groups. First, we have performed electrical maps 368 of complete LFCs with the intention to qualitatively evidence 369 differences in terms of electrical conductivity. In addition to 370 the electrical maps, I-V measurements were also performed. 371 These measurements were done in static mode at various lo-372 cations onto the LFCs. In order to minimize the well-known 373 light scattering effects from the AFM laser, which can induce 374 local photoconductivity [20], the laser was turned-off for a brief 375 moment before the *I*–V acquisition. 376

Representative c-AFM results obtained from a LFC processed 377 at 1.43 W are shown in Fig. 8(a). The upper part of the image 378 shows the topography map, whereas the lower part of the panel 379 corresponds to the local resistance map recorded while apply-380 ing a voltage of +2 V. In the latter, the darker zones indicate 381 the areas with a low local resistance, i.e., high conductivity. In 382 particular, the border of the contact shows the highest electrical 383 conductivities which decrease as you move to the center of the 384 contact. The highest local resistance was evidenced in outer re-385 gion of the LFC (region that has not been processed). C-AFM 386 data is in great agreement with Raman and PL data showed in 387 the first part of the work, where highly doped regions of the 388 contact processed at 1.43 W were detected at the border of the 389 contact. 390

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Fig. 8. (a) Topography (upper half) and local resistance (lower half) maps of a LFC processed at 1.43 W. (b) I-V characteristics of the selected points t1, t2, and t3 are represented. Additionally, an I-V curve (in blue) corresponding to a highly conductive area in a LFC processed at 1.1 W is also shown.

The I-V curves corresponding to the three points (t1, t2, and 391 t3) depicted in the local resistance map of Fig. 8(a) are repre-392 393 sented in Fig. 8(b). The curves have been calculated from an average of at least 20 curves per point. As expected from the 394 resistivity map, the curve recorded at point t1 is the one that 395 shows a higher conductivity. Moreover, it also shows a good 396 linearity evidencing an ohmic contact behavior between the di-397 amond tip and the sample. In contrast, the I-V curve recorded at 398 point t2 (central part of the contact) evidences lower conductiv-399 ity than that obtained at point t1. In addition, t2 curve shows a 400 rectifying behavior. This can be explained by a higher potential 401 barrier between the diamond tip and the less doped Si region. 402 Of course, this scenario is even more evident for the I-V curve 403 measured on the unprocessed region (t3). The potential barrier 404 between the diamond tip and the nonprocessed surface (with a 405 related doping density of about 5×10^{15} cm⁻³) enlarges, creating 406 a Schottky-like contact. In order to strengthen the consistency of 407 the measurements, another I-V curve obtained onto the highly 408 doped region of a contact processed at 1.1 W is also shown. As 409 it was expected, the I-V curve shows a lower conductivity than 410 the curve related to the LFC processed at 1.43 W. Again, the 411 412 symmetry of the curve confirms the ohmic-like behavior of the 413 contact between the tip and the highly doped sample region.

IV. CONCLUSION

In summary, the doping profiles in LFCs processed between 0.98 and 1.43 W in Al_2O_3 -passivated p-type c-Si wafers have been studied. The laser power used to process the LFCs has been

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found to play an important role in the distribution of the highly 418 doped regions. At powers around 1 W, the highly doped regions 419 that reach doping levels of 2×10^{18} cm⁻³ are preferentially lo-420 cated at the center of the LFCs. In contrast, for higher laser power 421 values, the level of doping increases (levels of around 3×10^{19} 422 cm^{-3} has been observed for contacts processed at 1.43 W), and 423 the location of the highly doped regions moves toward the border 424 of the contacts. The high spatial resolution associated with our 425 micro-Raman measurements has allowed to obtain consistent 426 doping density values. Hence, micro-Raman is preferably the 427 more appropriate tool to quantify doping levels with submicron 428 resolution. We consider an important result the observation of 429 microcrystalline-like features in the Raman spectra recorded at 430 specific points inside the LFCs, which suggests that the locally 431 molten Si fraction solidifies in microcrystalline manner. 432

Highly doped regions revealed by Raman measurements have 433 been further confirmed by micro-PL spectroscopy. Regions with 434 a higher doping density evidenced a blue shift of the PL emission 435 line, which we correlate with the Si band-gap renormalization 436 induced by the strong increase in doping. Despite the sample 437 volume measured by micro-PL is typically higher, and therefore, 438 the spatial resolution is lower, micro-PL measurements have also 439 shown a good sensitivity to doping variations. The high injection 440 conditions and the subsequent reduction of the photo-generated 441 carriers diffusion length [8] could favor to reduce the spatial 442 resolution of micro-PL measurements. 443

Finally, Raman and PL data have been further confirmed by 444 local *I–V* curves recorded through conductive-AFM. *I–V* characteristics obtained on highly doped areas featured an ohmiclike behavior, whereas *I–V* curves recorded at regions nonprocessed by laser, i.e., regions with lower doping level, revealed a Schottky-like behavior. 449

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Microscale Spatially Resolved Characterization of Highly Doped Regions in Laser-Fired Contacts for High-Efficiency Crystalline Si Solar Cells

A. Roigé, J. Alvarez, J.-P. Kleider, I. Martín, R. Alcubilla, and L. F. Vega

5 Abstract—Laser-fired contact (LFC) processes have emerged as a promising approach to create rear local electric contacts in p-type 6 crystalline silicon solar cells. Despite this approach has been suc-7 8 cessfully applied in devices showing efficiencies above 20%, there is still a lack of knowledge about some specific features of LFCs 9 10 at the submicron level. In this study, we used micro-Raman and microphotoluminescence (PL) spectroscopies to carry out a high-11 resolution spatially resolved characterization of LFCs processed 12 in Al2 O3 - passivated c-Si wafers. Relevant information concerning 13 features such as local doping distribution and crystalline fraction 14 15 of the laser-processed region has been obtained. In particular, interesting qualitative and quantitative variations concerning the 16 doping profile have been observed between LFCs processed at dif-17 ferent laser powers. Finally, conductive-atomic force microscopy 18 19 measurements have allowed to identify the existence of highly con-20 ductive zones inside the LFCs greatly correlated with highly doped 21 regions revealed by Raman and PL data. This study gives a detailed 22 insight about the LFCs characteristics at the submicron level and their possible influence on the performance of final devices. 23

Index Terms—Crystalline silicon, laser-fired contacts (LFCs),
 microphotoluminescence spectroscopy, micro-Raman spec troscopy.

I. INTRODUCTION

F ROM an industrial point of view, one of the most interesting crystalline silicon (c-Si) solar cell technologies to obtain high-efficiency devices is the passivated emitter and rear cell concept. Recently, the industrial implementation of this cell type has been significantly simplified by using the so-called laser fired contact (LFC) approach for the creation of the back contacts of the cell [1], [2]. This method is based on firing the

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rear Al metallization layer by a laser beam in order to create electrical point contacts between the Al layer and the silicon substrate through the passivation layer.

A key feature for the good operation of LFCs is the formation of an Al-doped p+ region under the contacted surface area. This is achieved by the diffusion of Al atoms from the predeposited Al layer into the molten Si. This p+ region not only creates a local back-surface field that induces a relatively low recombination velocity below the contacts, but also ensures a low-contact resistance.

LFC approach can be applied by using any of the dielectric layers that have demonstrated excellent c-Si passivating properties such as silicon oxide (SiO_2) [3], silicon nitride (SiN_r) 47 [4], amorphous-silicon carbide $(a-SiC_x)$ [5], and most recently, 48 aluminum oxide (Al_2O_3) [6]. In the case of using the latter pas-49 sivating material, an interesting alternative to the conventional 50 LFC process can be applied. In this case, the Al_2O_3 layer it-51 self can be used as Al-dopant source for the formation of the 52 p+ region, and hence, the LFC can be done directly onto the 53 Al₂O₃/c-Si, instead of being done onto the Al/dielectric/c-Si 54 stack. This approach enables a lower laser power operation in 55 comparison with conventional LFC process where higher laser 56 powers are needed to fire the aluminum through the dielectric 57 layer. These type of LFC processes have been already used to 58 fabricate solar cells showing efficiencies well above 20% [6]. 59

Despite the evident success in the implementation of the LFC 60 approach in real devices, there is still a lack of information about 61 specific features of LFCs such as the doping profile of the p+ 62 region, the level of induced-stress, and/or the structural prop-63 erties of the laser-processed region. The most likely reason for 64 that is the difficulty to find experimental techniques that match 65 a high-lateral resolution (below 10 μ m) and sensitivity to the 66 parameters wanted to be studied. Recently, a study of LFC cross 67 sections [7] have demonstrated that Raman and photolumines-68 cence (PL) spectroscopies in microconfiguration are techniques 69 that fulfill the mentioned requirements. 70

In this study, we have carried out high-resolution micro-71 Raman and micro-PL spectroscopy measurements on different 72 LFCs processed in Al₂O₃-passivated c-Si samples. Thanks to 73 the high lateral resolution down to 1 μ m achieved in our ex-74 periments, we have been able to perform a detailed study of 75 relevant LFC properties such as the doping profile, induced-76 stress, and crystallinity fraction, giving an important insight 77 about the LFC formation. Three LFCs processed at different 78 incident laser power have been studied in order to analyze the 79 influence of the laser power on the studied features. Finally, in 80

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order to complement the PL and Raman data, conductive-atomic
 force microscopy (c-AFM) measurements have been performed
 in order to study local resistance variations inside the LFCs.

It is worth to mention that the term LFC has been used since more than a decade to describe the firing of the predeposited aluminum through a dielectric layer. Despite the process used here is fundamentally different, its finality and application in solar cell devices is the same. For simplicity, we have maintained the term LFC to refer to our laser-processed locally doped regions.

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II. EXPERIMENTAL METHODS AND MATERIALS

91 Samples under study were based on 2.5 Ω ·cm boron-doped float-zone (FZ) crystalline Si (c-Si) wafers with a thickness of 92 250 μ m and (1 0 0) crystal orientation. c-Si wafers were pas-93 sivated by a 25-nm-thick aluminum oxide (Al₂O₃) film which 94 95 was grown by thermal atomic layer deposition. Laser fired spots 96 were processed on the top of the Al₂O₃-passivated c-Si sam-97 ples creating small apertures in the alumina layer and melting a small part of the underlying c-Si subsurface region. LFCs were 98 processed by a 1064 nm Nd:YAG lamp-pumped laser working 99 at 100 ns of pulse duration. Each contact is a consequence of 100 six pulses at a repetition rate of 4 kHz. Three different LFCs 101 processed with a laser power of 0.98, 1.1, and 1.43 W were 102 studied, corresponding to pulse energies of 245, 275, and 357.5 103 μ J. The laser beam shows a Gaussian profile with a beam waist 104 characterized by a radius of 70 μ m at the focus plane where all 105 the samples were processed. After laser processing and prior to 106 carry out the measurements, samples were immersed in an HF 107 1% solution bath during 40 s (or until obtaining an hydrophobic 108 silicon surface) in order to remove the Al₂O₃ layer. Addition-109 ally, three boron-doped FZ c-Si wafers with doping densities 110 of 1×10^{15} , 5×10^{18} , and 1×10^{20} cm⁻³ were used in order to 111 obtain reference Raman and PL spectra. 112

Micro-Raman and microphotoluminescence experiments 113 were carried out with a WITEC alpha300. A diagram of the 114 Witec equipment setup can be found in [8]. A diode-pumped 115 laser with a wavelength of 532 nm was used as an excitation 116 source resulting in a penetration depth of about 1 μ m. Micro-117 Raman and micro-PL measurements were performed with a 100 118 VIS (visible), NA (numerical aperture) = 0.9 and a $20 \times IR$ Х 119 (Infrared), NA = 0.45, respectively. The resulting beam spot 120 size on the sample surface is in diameter below 1 and 2 μm for 121 Raman and PL measurements, respectively. Raman scattering 122 signal was recorded through a 300-mm imaging spectrometer 123 equipped with both a 600 lines/mm and 1800 lines/mm grat-124 ing, and a 1024×127 CCD (charge-coupled device) camera 125 visible-optimized, whereas PL signal was collected through an 126 additional 300-mm spectrometer composed of two gratings (150 127 and 300 lines/mm) and a 1024×1 pixel linear InGaAs photodi-128 ode array optimized for spectroscopy applications in the range 129 1–1.7 μ m. It is worth to mention that the incoming laser power 130 on the sample surface for the Raman measurements was kept 131 below 3 mW. With our configuration, 3 mW was measured to 132 be the pumping limit to keep the photo-generated carrier den-133 sity below threshold and, therefore, to avoid Fano resonances 134 induced by high injection conditions [15]. 135

Local electrical measurements through the c-AFM technique 136 were performed using a Digital Instruments Nanoscope IIIa 137 Multimode AFM associated with the home-made conducting 138 probe extension called "Resiscope" [9]. This extension allows 139 us to apply a stable dc bias voltage (from -10 to +10 V) to the 140 sample and to measure the resulting current flowing through the 141 tip as the sample surface is scanned in contact mode, yielding a 142 local resistance map covering resistance values in the range 10^2 – 143 $10^{12} \Omega$. Current–Voltage (*I–V*) measurements are also permitted 144 with this extension. Highly boron doped diamond-coated Si 145 AFM cantilevers, with an intermediate spring constant of about 146 3 N/m, proved to be the most suitable AFM tips for making 147 electrical measurements on LFCs. Due to the AFM tip radius 148 $(\sim 50 \text{ nm})$, c-AFM measurements offer a much greater lateral 149 resolution. This latter depends on the electrical contact radius 150 between the tip and the surface. In the particular case of flat 151 surfaces, the electrical contact radius can be much smaller than 152 AFM tip radius. The probed depth remains in the nanoscale 153 range, but it is linked, among other parameters, to the applied 154 voltage and the local electrical transport properties. 155

III. RESULTS AND DISCUSSION 156

A. Doping Characterization by Micro-Raman Spectroscopy 157

Doping profiles in c-Si can be monitored by studying both 158 the Full Width at Half Maximum (FWHM) [10] and the Fano 159 resonance [11] of the first-order Si Raman peak. In particular, 160 Fano resonances are evident in the Si Raman spectra at hole 161 concentrations above 10^{18} cm⁻³ by a characteristic asymmetry 162 in the first-order Si Raman line. This asymmetry results from 163 the resonant interaction between discrete phonon states and a 164 continuum of hole states [12], [13]. The Raman peak line shape 165 can be described by the following expression [11]: 166

$$I(k) = I_0 \cdot \frac{[q + 2(k - k_{ph})/\Gamma]^2}{1 + [2(k - k_{ph})/\Gamma]^2}$$
(1)

where I_0 is a scaling factor, k_{ph} is the frequency associated to 167 the Raman peak maximum, Γ corresponds to the FWHM, and q168 is the asymmetry parameter, which is correlated with the doping 169 level of the sample being studied. The lower the q parameter, 170 the higher the doping level. The first-order Si Raman peak can 171 be also influenced by stress and/or by the material crystalline 172 fraction. The former can be monitored by the peak frequency 173 shift, whereas the latter is evidenced by a peak broadening from 174 the c-Si to the amorphous-Si state. 175

Fig. 1 shows the optical microscope images (left-hand side) 176 and the corresponding Raman peak width maps (right-hand side) 177 of the three LFCs under study processed at 0.98 (a) and (b), 178 1.1 (c) and (d), and 1.43 W (e) and (f). Maps were obtained 179 from the raw Raman peak width, not from the fitted Γ . The 180 corresponding LFC diameters were 43.8, 54.5, and 74.2 μ m, 181 respectively. For ensuring a good observation of the obtained 182 data, the microscope images and the Raman maps of the three 183 contacts have been represented with a slightly different scale. In 184 addition for clarity, the physical dimensions of the LFCs have 185 been represented in Raman maps by a green dotted circle. As 186 explained previously, the width of the first-order Raman peak 187

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Fig. 1. Optical microscope images (left-hand side) and Raman peak width maps (right-hand side) of the three LFCs under study processed at 0.98 (a) and (b), 1.1 (c) and (d), and 1.43 W (e) and (f). Brighter zones in the Raman peak width maps correspond to zones with higher doping density.

can be used to monitor the doping level of the sample under 188 study. Hence, the zones that evidence an increase of the Raman 189 peak width in Fig. 1 (brighter zones) are qualitatively correlated 190 with zones with a higher doping level. The LFC processed at 191 0.98 W evidences slightly higher levels of doping at the central 192 part of the contact. In contrast, the contact processed at 1.1 W 193 [see Fig. 1(d)] evidences a brighter concentric corona pointing 194 out a wider Raman peak and consequently an increase of the 195 doping level. Following the same trend, for the contact processed 196 using the higher laser power [see Fig. 1(f)], the border of the 197 contact is the area that evidences a higher level of doping. The 198 different Raman maps illustrated in Fig. 1 demonstrate that 199 the laser power plays an important role on the distribution of 200 201 the highly doped regions inside the contacts. More precisely, it seems that for higher laser powers, the highly doped regions 202 move toward the border of the contact. Two-dimensional depth 203 profiling across LFCs (maps not shown for space limitations) 204 revealed the same results. This fact corroborates that the features 205 of Raman maps shown in Fig. 1 were not affected by variations 206 in surface topography of LFCs. 207

The correlation between the Raman peak widening observed 208 in Fig. 1 and the expected increase in the doping density is con-209 firmed by data shown in Fig. 2. This figure shows the averaged 210 Raman spectra corresponding to the zones with higher doping 211 of images b, d, and f of Fig. 1. In particular, the averaged spectra 212 were calculated from the yellow-colored areas of Raman maps. 213 An averaged spectrum corresponding to an unprocessed area 214 (outer region of LFC) is also shown (yellow dashed line). In 215



Fig. 2. Averaged Raman spectra corresponding to the brighter zones of maps b, d, and f of Fig. 1. For comparison, an averaged Raman spectra corresponding to an unprocessed surface area has been also represented (yellow dashed line). The inset shows the Raman spectra recorded from the three reference c-Si wafers with different doping level.



Fig. 3. Raman spectra obtained at specific points inside LFCs processed at 1.1 W (r1, r2) and 1.43 W (r3). In addition to the first-order Raman peak, a second peak characteristic of microcrystalline silicon sets in at lower wavenumbers. For comparison, a Raman peak related to an unprocessed area (outer region of LFCs) is also depicted.

order to facilitate the observation of Fano resonances, Raman 216 spectra have been represented using a semilog scale. As it can 217 be observed, the Fano resonance is clearly identified for all Ra-218 man spectra except for the one obtained out of the LFC, which 219 shows a symmetric Raman line shape. This qualitatively con-220 firms that the brighter zones in maps of Fig. 1 are correlated 221 with areas with a higher doping level. The increase in doping 222 is also greatly confirmed by the inset, where the Raman spectra 223 recorded from three reference c-Si wafers with doping levels of 224 1×10^{15} , 5×10^{18} , and 1×10^{20} cm⁻³ clearly evidence the 225 same trend concerning the Fano resonance. Another important 226 feature observed in the main plot of Fig. 2 is that the LFCs 227 processed with a higher laser power have associated a higher 228 Fano asymmetry. Hence, the use of higher laser powers results 229 in LFCs with higher doping densities. 230

In order to get further important information about the LFCs 231 formation, we depict in Fig. 3 the Raman spectra recorded 232 at three specific points (r1, r2, and r3) inside two LFCs pro-233 cessed at 1.1 W (r1, r2) and 1.43 W (r3) (contact images and 234 point positions not shown). A fourth Raman spectrum corre-235 sponding to a nonprocessed surface area is also represented 236 as a reference. As it can be observed, in addition to the first-237 order c-Si Raman line positioned at 520.9 cm⁻¹, new Raman 238 bands can be identified at lower wavenumbers in the range be-239 tween 500 and 515 cm^{-1} . These latter bands are commonly as-240 signed to microcrystalline silicon [16], [17]. Indeed, the Raman 241



Fig. 4. Fitting using (2) of the Raman spectrum corresponding to the highlydoped region of the LFC processed at 1.1 W. Fit gave a q parameter of 59 which is correlated to a doping level of about 5.8×10^{18} cm⁻³.

spectra of microcrystalline-Si are currently decomposed into 242 three bands: crystalline (\sim 520 cm⁻¹), intermediate band (500– 243 515 cm⁻¹, usually interpreted as a signature of the grain bound-244 aries or small crystallites grain size <10 nm), and amorphous 245 (480 cm^{-1}) . The following decomposition is used to quantify the 246 crystalline fraction [18]. The observation of these new Raman 247 bands at specific points inside the LFCs suggests that molten Si 248 material fraction solidifies in a structure involving crystallites, 249 grain boundaries, and an amorphous phase, at least in specific 250 zones inside the contacts. However, the crystalline fraction in 251 these zones reveals to be high indicating a negligible amorphous 252 component. 253

The contribution of microcrystalline-Si components to the obtained Raman spectra is further confirmed by the fact that all Raman spectra recorded inside the LFCs could be significantly better fitted using a rewriting of (1) that considers a second Lorentzian function related to the contribution of the microcrystalline Si formation. In fact, the expression that has been used to fit the Raman data is the following:

$$I(k) = I_0 \cdot \frac{[q + 2(k - k_{ph})/\Gamma]^2}{1 + [2(k - k_{ph})/\Gamma]^2} + \frac{A}{1 + [2(k - k_m)/\Gamma_m]^2}$$
(2)

where A corresponds to the intensity, k_m is the frequency of 261 the peak maximum, and Γ_m is the peak width of the Raman 262 band related to the microcrystalline-like component. It is worth 263 to mention that the position of the second Lorentzian function 264 was limited to values between 505 and 517 cm^{-1} . As observed 265 in Fig. 4 for a LFC processed at 1.1 W, the fit using (2) shows 266 very good adjustment paving the way to obtain a reliable quan-267 tification about the doping level inside the LFCs. 268

Table I shows the q asymmetry parameters resulting from 269 the best fit of (2) to the Raman spectra related to the highly 270 doped regions of the three LFCs under study. Data were calcu-271 lated from at least two LFCs for each one of the three values of 272 laser power. The obtained q parameters clearly illustrate that the 273 higher the laser power, the higher the doping density. According 274 to the calibration tables reported in [10] and [11], we have ob-275 tained maximum doping levels in the range of $1.17-3.83 \times 10^{18}$, 276 $4.58-6.06 \times 10^{18}$, and $2.15-5.02 \times 10^{19}$ cm⁻³ for the LFCs pro-277 cessed at 0.98, 1.1, and 1.43 W, respectively. It is important to 278

TABLE I q Asymmetry Parameter Obtained From the Fitting of (2) to the Averaged Raman Spectra Related to the Highly Doped Regions of the Three LFCs Under Study.

power (W)	q (arb.units)	doping ref. [10] $(\times 10^{18} \text{ cm}^{-3})$	doping ref. [11] $(\times 10^{18} \text{ cm}^{-3})$
0.98	90 ±7	3.13 - 3.83	1.17 – 2.35
1.10	61 ± 4	5.19 - 6.06	4.58 - 6.03
1.43	16 ± 2	21.49 - 27.93	42.19 - 50.17

The corresponding doping densities were calculated using the calibration tables reported in [10] and [11].



Fig. 5. (a) Raman spectra center of mass map of a LFC processed at 1.43 W. (b) Specific Raman spectra associated with points s1, s2, and s3 are also plotted.

remark that the intensity of the second Lorentzian peak related to the multicrystalline component was observed to increase with higher laser powers. This suggests that the use of higher laser powers decreases the crystalline fraction of the solidified Si volume. 283

Fig. 5(a) shows the Raman spectra center of mass map of a 284 LFC processed at 1.43 W. The Raman spectra of the selected 285 points (s1, s2, and s3) are represented in Fig. 5(b). The center 286 of mass was calculated considering a frequency range between 287 480 and 560 cm^{-1} ; thus, as confirmed by Raman spectra of 288 Fig. 5(b), it could be qualitatively correlated with the frequency 289 shift of the first-order Si Raman peak. The first-order Raman 290 line of s1, s2, and s3 Raman spectra is centered at 520.8, 519.3, 291 and 518.7 $\rm cm^{-1}$, respectively. Notice that the center of mass 292 values represented by the color scale bar of Fig. 5(a) are shifted 293 toward higher frequencies respect the Raman peak position val-294 ues mentioned previously. This is induced by the contribution 295 of the Fano resonance which moves de center of mass toward 296 higher energies respect the peak maximum. As it can be seen, 297 the Raman peak position suffers a red shift of about 2 cm^{-1} at 298 the border of the contact. Interestingly, areas of the contact that 299 show such a red shift exactly match with areas of the 1.43 W 300 LFC that evidence higher levels of doping [see Fig. 1(f)]. It has 301 been reported, that Raman spectra obtained from samples with 302 doping levels above 5×10^{18} cm⁻³ not only exhibit the so-called 303 Fano resonance, but also show a red shift in the Raman peak 304 maximum [19]. The expected theoretical peak shift induced by 305 an increase in doping satisfies: 306

$$k = k_0 + \frac{\Delta\Gamma}{2\,q} \tag{3}$$



Fig. 6. PL center of mass maps of LFCs processed at (a) 0.98 W and (b) 1.43 W. The green dotted circles delimit the physical dimensions of the LFCs.

where k_0 is the peak position of the bulk un-doped and stress 307 free c-Si and $\Delta\Gamma$ is the change in the Raman peak width due 308 to doping. The expected theoretical peak shifts resulting from 309 (3) for a q parameter of 16 (see Table I) takes values of about 310 0.5 cm^{-1} . These theoretical values are significantly lower than 311 those observed in Fig. 5, i.e., about 2 cm^{-1} . This fact suggests 312 that in addition to the red shift induced by an increase of the 313 doping level, a second contribution in the Raman shift is also 314 present. We correlate this second contribution with stress pos-315 sibly induced by the laser process. LFCs processed at 0.98 and 316 1.1 W do not show any significant red shift in the first-order 317 Raman peak maximum. Thus, the level of laser power used to 318 process the LFCs probably plays an important role in the level 319 of stress induced by the laser process. 320

321 B. Doping Characterization by

322 Photoluminescence Spectroscopy

Band-to-band photoluminescence spectroscopy senses the ra-323 diative recombination between photo-generated electrons in the 324 conduction band (CB) and the corresponding holes in the va-325 lence band (VB). As an increase in doping density induces a 326 reduction of the energy gap between CB and VB, PL has been 327 proven as a reliable tool for monitoring the band-gap shift in 328 heavily doped c-Si [14]. In this sense, micro-PL spectroscopy 329 330 is also capable to characterize the high doping levels expected inside the LFCs. In fact, micro-PL has been applied to charac-331 terize the doping density in laser-induced highly doped regions 332 cross sections [7]. In our study, we study the position and line 333 shape of the PL emission line by monitoring the center of mass 334 of the PL spectra recorded inside the LFCs. 335

Fig. 6 shows the PL center of mass maps corresponding to 336 the LFCs processed at 0.98 (a) and 1.43 W (b). The averaged 337 PL spectra obtained from the brighter zones of the PL maps 338 are illustrated in Fig. 7. As it can be seen, the shift of the 339 PL spectra center of mass revealed by the color scale bars of 340 Fig. 6 is linked to an increase of the PL intensity at lower 341 energies. In particular, the PL spectrum related to the 0.98 W 342 LFC evidences a slight increase of the left PL spectrum shoulder, 343 whereas the PL spectrum related to the 1.43 W LFC shows a 344 significantly higher increase of the left PL spectrum shoulder 345 plus a blue shift in the PL emission maximum. We correlate 346 this shift of the PL line with a Si band-gap renormalization 347 induced by a strong increase of doping in the measured material 348 volume. The increase in the doping density is further confirmed 349 by the inset of Fig. 7 which illustrates the PL spectra recorded 350 from c-Si wafers with doping levels of 1×10^{15} , 5×10^{18} , and 351



Fig. 7. Averaged PL spectra corresponding to the highly doped regions (yellow-colored regions) of PL center of mass maps a (0.98 W) and b (1.43 W) illustrated in Fig. 6. Additionally, a PL spectra recorded out of the processed LFC regions is also represented. The inset plot shows the PL spectra corresponding to three reference c-Si wafers with different doping level.

 1×10^{20} cm⁻³. As it can be seen, the inset and the main plot 352 show the same trend. For all these reasons, we confirm that 353 the brighter zones of the PL maps of Fig. 6 have associated 354 a higher doping level. Interestingly, the two represented PL 355 maps greatly correlate with the homologous Raman width maps 356 of Fig. 1, demonstrating the successful application of micro-357 Raman and micro-PL techniques for studying doping-density 358 variations above 1×10^{18} cm⁻³ with submicron resolution. 359

C. Laser-Fired Contact Characterization by Conductive-Atomic Force Microscopy

Finally, the study of LFCs was completed by their character-362 ization by means of c-AFM measurements. The aim of these 363 studies is to analyze if the laser-processed material volume 364 shows preferential conductive zones, and if that is the case, 365 to study their correlation with the highly doped regions deduced 366 from Raman and PL data. C-AFM measurements have been di-367 vided in two groups. First, we have performed electrical maps 368 of complete LFCs with the intention to qualitatively evidence 369 differences in terms of electrical conductivity. In addition to 370 the electrical maps, I-V measurements were also performed. 371 These measurements were done in static mode at various lo-372 cations onto the LFCs. In order to minimize the well-known 373 light scattering effects from the AFM laser, which can induce 374 local photoconductivity [20], the laser was turned-off for a brief 375 moment before the *I*–V acquisition. 376

Representative c-AFM results obtained from a LFC processed 377 at 1.43 W are shown in Fig. 8(a). The upper part of the image 378 shows the topography map, whereas the lower part of the panel 379 corresponds to the local resistance map recorded while apply-380 ing a voltage of +2 V. In the latter, the darker zones indicate 381 the areas with a low local resistance, i.e., high conductivity. In 382 particular, the border of the contact shows the highest electrical 383 conductivities which decrease as you move to the center of the 384 contact. The highest local resistance was evidenced in outer re-385 gion of the LFC (region that has not been processed). C-AFM 386 data is in great agreement with Raman and PL data showed in 387 the first part of the work, where highly doped regions of the 388 contact processed at 1.43 W were detected at the border of the 389 contact. 390

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Fig. 8. (a) Topography (upper half) and local resistance (lower half) maps of a LFC processed at 1.43 W. (b) *I–V* characteristics of the selected points t1, t2, and t3 are represented. Additionally, an *I–V* curve (in blue) corresponding to a highly conductive area in a LFC processed at 1.1 W is also shown.

The I-V curves corresponding to the three points (t1, t2, and 391 t3) depicted in the local resistance map of Fig. 8(a) are repre-392 sented in Fig. 8(b). The curves have been calculated from an 393 394 average of at least 20 curves per point. As expected from the resistivity map, the curve recorded at point t1 is the one that 395 shows a higher conductivity. Moreover, it also shows a good 396 linearity evidencing an ohmic contact behavior between the di-397 amond tip and the sample. In contrast, the I-V curve recorded at 398 point t2 (central part of the contact) evidences lower conductiv-399 ity than that obtained at point t1. In addition, t2 curve shows a 400 rectifying behavior. This can be explained by a higher potential 401 barrier between the diamond tip and the less doped Si region. 402 Of course, this scenario is even more evident for the I-V curve 403 measured on the unprocessed region (t3). The potential barrier 404 between the diamond tip and the nonprocessed surface (with a 405 related doping density of about 5×10^{15} cm⁻³) enlarges, creating 406 a Schottky-like contact. In order to strengthen the consistency of 407 the measurements, another I-V curve obtained onto the highly 408 doped region of a contact processed at 1.1 W is also shown. As 409 it was expected, the I-V curve shows a lower conductivity than 410 the curve related to the LFC processed at 1.43 W. Again, the 411 symmetry of the curve confirms the ohmic-like behavior of the 412 413 contact between the tip and the highly doped sample region.

IV. CONCLUSION

In summary, the doping profiles in LFCs processed between 0.98 and 1.43 W in Al_2O_3 -passivated p-type c-Si wafers have been studied. The laser power used to process the LFCs has been

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found to play an important role in the distribution of the highly 418 doped regions. At powers around 1 W, the highly doped regions 419 that reach doping levels of 2×10^{18} cm⁻³ are preferentially lo-420 cated at the center of the LFCs. In contrast, for higher laser power 421 values, the level of doping increases (levels of around 3×10^{19} 422 cm^{-3} has been observed for contacts processed at 1.43 W), and 423 the location of the highly doped regions moves toward the border 424 of the contacts. The high spatial resolution associated with our 425 micro-Raman measurements has allowed to obtain consistent 426 doping density values. Hence, micro-Raman is preferably the 427 more appropriate tool to quantify doping levels with submicron 428 resolution. We consider an important result the observation of 429 microcrystalline-like features in the Raman spectra recorded at 430 specific points inside the LFCs, which suggests that the locally 431 molten Si fraction solidifies in microcrystalline manner. 432

Highly doped regions revealed by Raman measurements have 433 been further confirmed by micro-PL spectroscopy. Regions with 434 a higher doping density evidenced a blue shift of the PL emission 435 line, which we correlate with the Si band-gap renormalization 436 induced by the strong increase in doping. Despite the sample 437 volume measured by micro-PL is typically higher, and therefore, 438 the spatial resolution is lower, micro-PL measurements have also 439 shown a good sensitivity to doping variations. The high injection 440 conditions and the subsequent reduction of the photo-generated 441 carriers diffusion length [8] could favor to reduce the spatial 442 resolution of micro-PL measurements. 443

Finally, Raman and PL data have been further confirmed by 444 local *I–V* curves recorded through conductive-AFM. *I–V* characteristics obtained on highly doped areas featured an ohmiclike behavior, whereas *I–V* curves recorded at regions nonprocessed by laser, i.e., regions with lower doping level, revealed a Schottky-like behavior. 449

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