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Photoemission investigation of the alkali-metal-induced two-dimensional electron gas at the Si(111)(1×1):H surface

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We investigate the formation of a two-dimensional electron gas (2DEG) at the hydrogen-passivated silicon (111) surface exposed to tiny amounts of alkali metals (K and Cs) by means of high-resolution ultraviolet photoemission spectroscopy. The accumulation layer derives from the quantization and filling of bulk states located around the conduction-band minimum. Direct photoemission from these states results in a well-defined and structureless feature, which becomes huge when the alkali metal is deposited at low temperature (150 K), indicating a much higher charge transfer associated with the growth at low temperature. Its shape is characterized by a tail which is attributed to the broadening of the 2DEG density of states due to the random fields set up by the ionized alkali metal at the surface, providing direct experimental evidence of tailing of two-dimensional subbands at a free semiconductor surface.

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I. INTRODUCTION

Low-dimensional semiconductor structures have been the subject of a wide range of studies during the last two decades. Their importance is due to the number of modern devices, such as metal-oxide semiconductors, heterojunctions, quantum-wells, and superlattices, which are based on these structures and which therefore derive their properties from the characteristics of the two-dimensional electron gas (2DEG).[1] A 2DEG can be created at a free semiconductor surface by the accumulation of electronic charge deriving from adsorbate atoms or from defects, as observed in the case of small gap III-V semiconductors such as InAs and InSb.[2,3,6] Recently, due to the high luminosity and resolution of modern electron analyzers, direct photoemission from the 2DEG in these systems can be measured with great precision, resulting in a feature observed in the energy distribution curve (EDC) around the Fermi level. The EDC's thus obtained are in excellent agreement with the calculated electronic structure and density of states, directly proving the quantization of the charge accumulation layer and the accuracy of its formal description.[4,5] Despite the attention devoted to small gap III-V semiconductors and the large amount of papers dealing with the interaction of silicon surfaces with various kind of adsorbates, a detailed photoemission investigation of the 2DEG formed at the surface of elemental semiconductors is still lacking. Alkali-metal (AM) deposition on clean reconstructed Si(111) surfaces is known to induce the formation of a depletion layer.[7] An accumulation layer is instead induced by deposition of a small amount of AM on the clean Si(100)−(2×1),[8] and on the "passivated" As(1×1)/Si(111),[9] As(1×1)/Ge(111),[10] Na(3×1)/Si(111),[11] B(1×1)/Si(111),[12] and H(1×1)/Si(111) (Refs. 13 and 14) surfaces. On the clean Si(100) and on the As-passivated (111) surfaces, a feature has been observed at the Fermi level and attributed to the partial occupation of a substrate empty surface state, while on the Na(3×1)/Si(111) and on the hydrogenated H(1×1)/Si(111) no measurements detecting the expected emission around the Fermi level have been reported so far.

In the present paper we present a detailed high-resolution (HR) ultraviolet photoemission spectroscopy (UPS) investigation of the 2DEG formation at the hydrogen-passivated Si(111) surface exposed to small amounts of alkali metals, focusing our attention on the emission from the accumulated electron gas. An intense feature is observed at the Fermi level, which is attributed to the filling of substrate empty bulk states. Dosing the AM at low temperature (150 K) results in a giant emission, whose intensity is more than one order-of-magnitude higher than that detected at room temperature (RT). This shows that the charge transfer is strongly enhanced at low temperature (LT), probably because of the different growing conditions when the AM surface diffusivity is lowered. Finally, the high-energy resolution and luminosity of the electron analyzer allowed us to study the shape of the feature. From comparison with recent calculations[15,16] we derived evidence of the broadening of the 2DEG density of states due to the random fields set up by the ionized AM atoms at the surface, already known to produce a strong inhomogeneity of the surface band bending.[17]

II. EXPERIMENT

The Si substrate used in the experiment was of *n* type with a doping concentration of about 9×10^{15} atoms/cm^3. The hydrogenated surfaces were obtained by chemical etching in HF and NH$_4$F as reported by Dumas and Chabal.[18] The surfaces were then introduced in the UHV system by a load lock soon after the last chemical etching.

HR-UPS measurements were carried out in a system consisting of two connected chambers (preparation and analysis), with a base pressure of 7×10^{-9}Pa (7×10^{-11} mbar), in which different kinds of electron spectroscopies such as high-resolution electron-energy loss, HR-UP, x-ray photoemission, and Auger electron, can be performed. Photoemission spectra excited by He-I (21.218 eV) and He-II (40.814 eV) UV radiation were measured by means of a SCIENTA

SES 200 hemispherical analyzer, with an overall energy resolution between 20 and 40 meV and an angular acceptance of about ±6 °.

From the position of the valence-band maximum (VBM), it was possible to deduce an "intrinsic" upward band bending of about 0.2 eV on the clean surface, probably due to a small amount of disorder on the surface. In fact the surface valence-band edge was found at about 0.7-eV below the Fermi level, while on the basis of the doping level a value of about 0.9 eV was expected for the bulk.

The alkali metals were evaporated from well-outgassed SAES Getters dispensers, in a vacuum that never exceeded 3×10^{-8} Pa. Depositions and measurements were done at RT and at 150 K (LT).

The amount of deposited metal was obtained from the intensity of the K $3p$ or Cs $5p$ core lines excited by He-II photons. These measurements showed that at RT the AM coverage saturates at a certain value, which is assumed to be the reference for the coverage and is referred to in the following as $\Theta=1$. It was then possible to convert the time scale into a coverage scale.

III. RESULTS

The valence-band (VB) photoemission spectrum of the clean Si(111)(1×1)−H surface, excited by He-I radiation for an electron takeoff angle of 28 °, is shown in Fig. 1. The three features typical of the clean surface can be identified at about 3.9, 5.9, and 7.9 eV of binding energy. These features are attributed to a bulk state, to the saturated dangling bonds (SiH), and to a surface resonance (SR), respectively.[19,20] The amount of deposited K is indicated as a fraction of the saturation coverage, relating the exposure time to the coverage by means of the calibrating curve shown in the inset of Fig. 1.

The evolution of the valence band in the first stages of potassium deposition is characterized by an almost rigid energy shift of the whole spectrum towards higher binding energy and a slight intensity reduction and broadening of the SiH peak and of the small shoulder located on its right side, deriving from the backbonds of the surface silicon atoms.[20] The most interesting feature, however, is the small peak crossing the Fermi level—indicated by "*F*" in Fig. 1—which appears for coverages higher than 0.03 and is more visible on the right side of Fig. 1, where the Fermi-level region is magnified. We focus on this feature in the following to elucidate its origin.

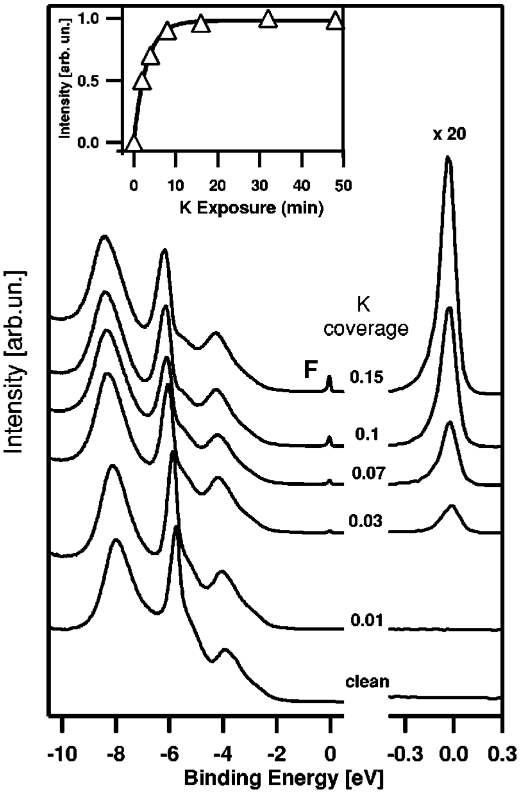

FIG. 1. Valence-band spectra (He-I-K_α, $h\nu=21.218$ eV) as a function of potassium coverage taken at 28 ° from the surface normal along the $\overline{\Gamma M}$ direction. Deposition and measurements have been taken at RT. The Fermi-level zone has been magnified on the right, in order to evidence the Fermi level emission. The inset shows the K $3p$ core level as a function of the exposure time.

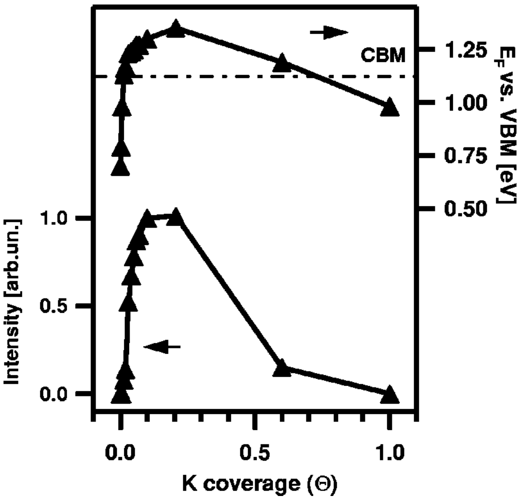

FIG. 2. Surface Fermi-level position (right scale) and intensity (left scale) of the Fermi-level emission peak (*F*) as a function of coverage.

The shift of the valence band corresponds to the band bending induced by the AM adsorption. The SiH-peak shift vs K coverage, taken as a measure of the band bending induced by the alkali metal, is reported in Fig. 2 (top curve). Starting from the lowest coverage ($\Theta\approx0.01$) the Fermi level rapidly moves upwards, enters in the conduction band, reaching the maximum shift (0.55 eV) for $\Theta\approx0.15$, then slowly moves back towards the bottom of the conduction band that is crossed at $\Theta\approx0.7$. Therefore, for coverages between 0.03 and 0.7 the Fermi level stays inside the conduction band, reaching 0.23 eV above the conduction-band minimum (CBM) for $\Theta\approx0.15$, meaning that an accumulation layer occurs at the surface. The bottom curve in Fig. 2 is a plot of the *F*-peak intensity as a function of K coverage, showing that the range of existence of the *F* peak corresponds to the presence of the Fermi level inside the conduction band. We therefore deduce that this peak is the emission

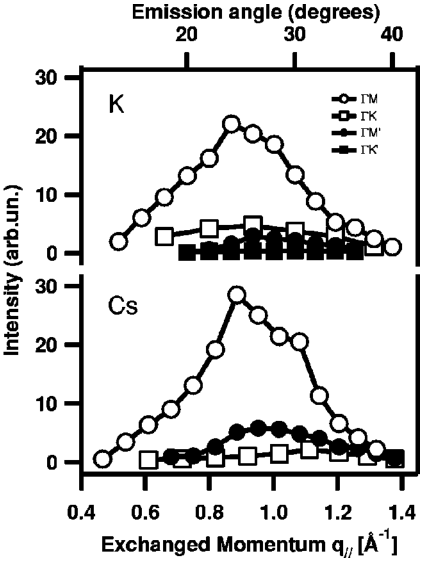

FIG. 3. Intensity of the Fermi-level peak as a function of the surface parallel wave-vector component of the emitted electrons. The emission angles corresponding to M and K points are 27 ° and 31 °, respectively.

from states—normally empty—whose filling is induced by the adsorbate.

An identical peak appears if cesium is deposited on Si(111)(1×1)−H. The coverage dependence is the same described for potassium. In both cases the peak has an asymmetrical shape, with a tail on the high binding-energy side, which is also independent from the amount of deposited metal, i.e., from its intensity. An interesting characteristic of the F emission is the strong angular dependence of its intensity, whereas neither its shape nor its position are apparently affected by the emission angle. Figure 3 shows that the intensity along the $\overline{\Gamma M}$ direction is about one order-of-magnitude higher than those along $\overline{\Gamma M'}$, $\overline{\Gamma K}$, and $\overline{\Gamma K'}$ (where the primed directions are the opposite with respect to Γ of the nonprimed ones[19]). Furthermore, along $\overline{\Gamma M}$, the intensity reaches its maximum when the electron wave vector has values around 0.85–0.95 Å^{-1}, which corresponds to the minimum of the Si(111) conduction band projected on the surface Brillouin zone.[19]

Remarkable is the effect of the substrate temperature on the intensity and position of the VB and the F-peak features in these systems. Figure 4 shows the VB spectra taken before and after cooling the clean sample and then depositing K at LT. The cooling of the clean substrate from RT to 150 K shifts the VB by 140 meV towards higher binding energies, in agreement with the expected temperature dependence of the Fermi level in an n-doped silicon crystal[21] in the absence of any pinning, indicating a very small density of defect states on the clean surface. Low-temperature deposition of a small K quantity ($\Theta = 0.1$) on the hydrogenated Si surface results in a giant emission at the Fermi level (Fig. 4, curve c) which is 20 times higher than at RT. Corresponding to this large emission at the Fermi level, a further shift of the main features occurs. The large band bending allows one to see that the shift is not rigid, but bulk and surface features are differently shifted. The inset of Fig. 4 reports the different Fermi-level positions with respect to the bulk silicon band structure deduced from the shifts of the three main VB features. At the largest accumulation, the shift corresponds to a Fermi-level position well above the conduction-band minimum. It amounts to 350 meV for the SR and the saturated dangling bonds (SiH), and to 150 meV for the bulk state. Even at room temperature the bulk and surface shifts were not the same, showing a difference which increases with band bending, reaching a maximum value of 120 meV. This discrepancy is related to the different nature of the states originating from the different valence-band structures. In fact, while the binding energy of the surface features is determined by the band bending at the surface, where it reaches its largest value, the position of the bulk feature is an average over the whole electron escape depth, and therefore results are smaller. A similar effect influences the band bending in the plane of the surface, producing a broadening and an intensity decrease of all the features. The effect is perhaps best visible on the SiH peak, which is the narrowest. Due to the superposition of components differently shifted in energy, this feature broadens and its height decreases, although the area is conserved. This effect of the band bending inhomogeneity is consistent with the analysis of the core line photoemission spectra recently performed on this same system.[17] That work showed that in the submonolayer regime, the band bending at the surface is described by a nearly Gaussian distribution having a full width at half maximum (FWHM) of about 300 meV. Moreover, that analysis showed that the mean band bending value decreases from the surface to the

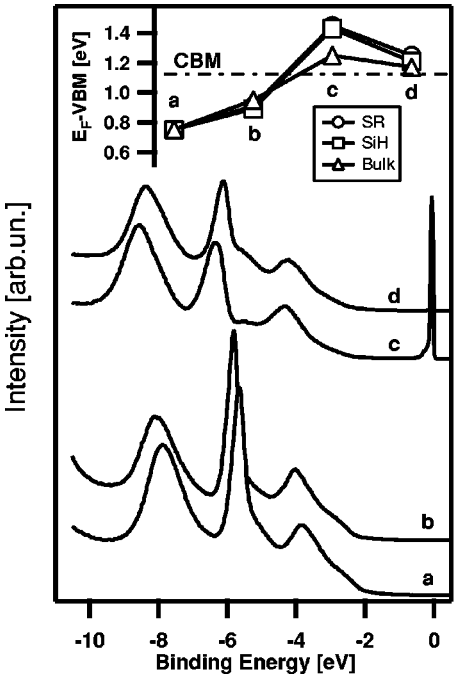

FIG. 4. Valence-band spectra (He-I-K_α, $h\nu = 21.218$ eV, taken at 28 ° from the surface normal along the $\overline{\Gamma M}$ direction) and surface Fermi-level position of (a) a clean surface at RT, (b) a clean surface at 170 K, and (c) after dosing K ($\Theta = 0.1$) onto the surface at LT and (d) the same conditions as in (c) after exposure to the residual atmosphere for about 2 h.

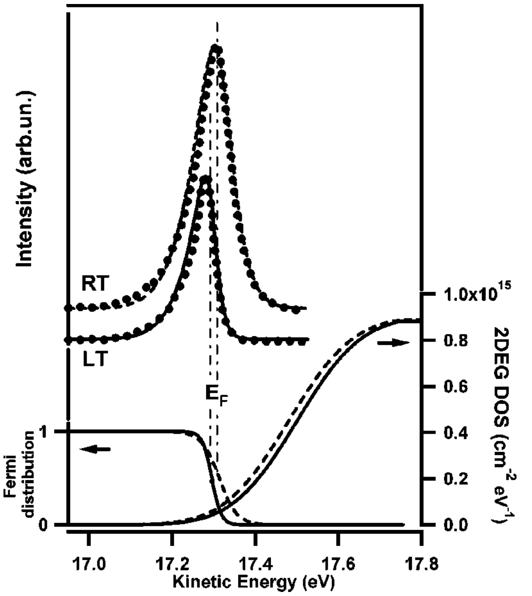

FIG. 5. Upper panel: Detail of the Fermi-level peak induced by dosing potassium ($\Theta=0.1$) at RT measured both at RT and LT. Experimental (dots) and calculated (solid line) spectra result from the fit based on the density-of-states (DOS) profile expected for a 2DEG subject to random potentials. Lower panel: the DOS profile and Fermi-Dirac statistical distribution function corresponding to the calculated spectra. The fits correspond to an accumulated charge density of 5.2×10^{12} (RT) and 2.3×10^{12} cm^{-2} (LT).

bulk. At the fifth silicon plane below the surface (about 6 Å), the band bending is 250-meV smaller than at the surface. The electron escape depth corresponding to the bulk feature is about 6 Å . A simulation performed by summing the contributions deriving from ten planes and assuming a linear dependence of the band bending decrease of 50 meV per Si plane leads to a shift of the bulk feature of 120 meV, in good agreement with the experiment.

The cooling of a surface previously exposed to K ($\Theta=0.15$) at room temperature leaves practically unchanged the VB spectrum (not shown), a very different behavior compared to that seen by depositing at low temperature. At variance with the clean surface, in this case the energy shift is within measurement uncertainty, pointing out the substantial Fermi-level pinning at the surface, now kept in place by the high density of surface states of the 2DEG.

The shape of the *F* peak also shows a temperature dependence. The peak induced by an AM deposition at RT ($\Theta=0.1$) measured at RT and at 150 K (LT) with an overall energy resolution lower than 20 meV is shown in Fig. 5. The low-energy tail is practically unaffected by temperature, while the positions of the maximum and the high-energy side strongly change with cooling, because of the narrowing of the Fermi-Dirac distribution function. The *F*-peak FWHM is around 120 and 90 meV at RT and LT, respectively. The temperature lowering produces a small shift (15 meV) of the Fermi level towards lower kinetic energies, the origin of which is still unclear.

IV. DISCUSSION

The experimental results presented here show that the deposition of very small amounts of AM onto the hydrogen-passivated silicon (111) surface induces a strong downward band bending, shifting the valence band almost rigidly. The Fermi level enters into the conduction band and previously empty substrate states are filled, giving rise to a photoemission peak at the Fermi level. A strict correlation is observed between the surface band bending and the intensity of the *F* peak, since this emission is present whenever the Fermi level enters the conduction band and disappears when the Fermi level exits. Furthermore, the independence of the *F* peak from the specific AM (Cs or K) indicates that it derives from electronic states of the substrate. But still we do not know the states from which the electrons originate. There are two possibilities:

(i) "true" surface empty states of the substrate—related to the H-Si bond, as in the case of As-terminated Si(111) (Ref. 9) or Ge(111);[10]

(ii) an "electrostatically confined" two-dimensional electron gas (2DEG) produced by the AM ionization, in which the states are the substrate conduction-band states quantized along the *z* direction by the potential setup by the AM ions and the screening electrons.

We will shortly see that the correct answer is (ii). The angular dependence of the *F*-peak intensity reflects the dispersion of the states originating from the Fermi emission. The experiment (Fig. 3) shows that the intensity along the $\overline{\Gamma M}$ direction is about one order-of-magnitude higher than those along $\overline{\Gamma M'}$, $\overline{\Gamma K}$, and $\overline{\Gamma K'}$. The maximum of the *F*-peak intensity is reached at the wave vector corresponding to the minimum of the conduction band projected along the (111) direction,[22] and its width is comparable to that of the band edge in the same point. Moreover, we observe that for the unreconstructed surface the directions $\overline{\Gamma M}$ and $\overline{\Gamma K}$ are equivalent to their opposites ($\overline{\Gamma M'}$ and $\overline{\Gamma K'}$), while this is not true for the bulk, where the symmetry is strictly trigonal,[20,22] ruling out the fact that the *F* peak may originate from surface states. On the other hand, calculations performed on the hydrogenated Si(111) surface find hydrogen-induced empty surface states only 2-eV above the VBM,[23] whereas the first state detected above the CBM by inverse photoemission is a resonance with bulklike character. This is located 2.4-eV above the VBM, so it is too high in energy to explain the *F* emission. In addition, the wave vector corresponding to its minimum does not match with our measurements, being located around 0.5 $\overline{\Gamma M}$.[24] These findings indicate that the *F* peak originates from the bulk states located around the conduction-band minima, similarly to the InAs and InSb (110) systems.[25] In those cases, however, the emission at the Fermi level had a very different shape, showing the staircase structure characteristic of the density of states of a two-dimensional electron gas (2DEG-DOS), with each step height given by $(g_v m^*)/(\pi\hbar^2)$, where g_v is the valley degeneracy.[1] On the other hand, a structureless Fermi emission is expected when the density of states is sufficiently high to allow the allocation of all the electrons constituting the 2DEG in the first subband. This hypothesis agrees with the much greater density of states around the CBM in Si with respect to InAs and InSb, derived from the higher effective mass of electrons and from the valley degeneracy.[1] However, the progressive filling of the subband is expected to be reflected in the *F*-peak width, but this effect is masked by its large intrinsic value (≈ 100 meV). The *F*-peak intrinsic width is represented by the left-hand-side tail, while the right-hand side is due to the thermal broadening of the Fermi-Dirac distribution. The experiment has shown that this tail is independent of (i) the specific alkali metal, (ii) the coverage, (iii) the temperature, and (iv) the photoelectron wave vector. A possible peak broadening source is the hole lifetime. Assuming the filling of a single subband, we tried to reproduce the *F*-peak shape. To account for the finite hole lifetime $(1/\Gamma)$, the ideal staircaselike shape of the 2DEG-DOS has to be broadened by convoluting it with a Lorentzian. This leads to a DOS profile expressed by $[(g_v m^*)/(\pi\hbar^2)]\{\pi/2+\arctan[(E-E_0)/(\Gamma/2)]\}$, which has to be multiplied by the Fermi-Dirac distribution probability to obtain the expected line shape. The energy-level position (E_0) must correspond to an accumulation value of the order of that found in a previous work on the same system,[13] that is, about 4×10^{12} cm^{-2}. This constraint, together with the high DOS value, corresponds to a very limited filling of the low-energy-side tail. The slow decay in energy of this functional form does not allow for an acceptable fit of the *F* peak, ruling out the possibility that a Lorentzian form may describe the main broadening mechanism. On the other hand, since the 2DEG is not degenerate, the main contribution to the hole lifetime is the same as that determining the carrier mobility, which is expected to be about 400 cm^2 V^{-1} s^{-1}, corresponding to $\tau_e^{-1}\simeq 15$ meV,[1,26,27] a value too small to explain the *F*-peak width. This conclusion is confirmed by the invariance of the tail when the temperature is lowered from 300 K to 150 K (Fig. 5), whereas the mobility is expected to double.[26]

A completely different explanation for the *F*-peak line shape is the DOS broadening induced by the random potentials produced by the alkali-metal ions. This is a well-known topic concerning heavily doped semiconductors,[28] in which the random potentials deriving from the ionized dopant atoms induce band tails that narrow the band gap. In two-dimensional systems, extensive magnetotransport investigations performed on metal-oxide semiconductor structures and multiple quantum wells[30] enabled discrimination between the scattering time determining the mobility and the relaxation time of the interacting electron gas.[29] Recently, Quang and Tung[15] calculated the DOS of a 2DEG subject to random fields. They first performed the calculation in the semiclassical approximation,[15] then treated deep tails by using a fully quantum-mechanical approach.[16] These studies provide an analytical form for the DOS profile in which the error function, erf(x), predominates on the low-energy side. Therefore we tried to reproduce the *F* peak by using the following expression:

$$y=y_0+\frac{g_v m}{2\pi\hbar^2}\left[1+\mathrm{erf}\left(\frac{E-E_0}{\gamma\sqrt{2}}\right)\right],$$

where γ is the root mean square (rms) of the random-field strength.

The results are reported in Fig. 5, superposed to the experimental spectra. The RT and LT spectra are relative to the same surface, first K covered and measured at RT, then cooled at LT and measured again. The fit has been performed on the RT spectrum by varying E_0 and γ, imposing a charge-density value around that expected on the basis of the high-resolution electron-energy-loss results.[13] Apart from the small Fermi-level shift adjustment and the use of the corresponding k_BT value, the LT spectrum has been reproduced by changing only the subband energy location in order to fit the intensity, whereas the random-field strength value ($\gamma=122$ meV) was kept the same. We used $(g_v m^*)/(\pi\hbar^2)=9\times10^{14}$ cm^{-2} eV^{-1} as the DOS value.[1] The fit is in good agreement with the experiment and also the γ value agrees with other independent results, as we see in the following. As mentioned above, a recent investigation of the band bending inhomogeneity on this same system[17] has shown that the statistical distribution of the surface band bending value in the submonolayer regime is described by a bell-shaped function which can be approximated by a Gaussian having a FWHM of about 300 meV. This width is independent of the coverage. γ is a measure of the width of the statistical distribution of the potential value. From its definition (rms value of the random-field strength), it follows that for a gaussian distribution its value is $\gamma=0.425$ FWHM. A distribution having FWHM$=300$ meV corresponds to $\gamma=127$ meV, in very good agreement with the results presented above.

Let us notice that the subband level (E_0) is located above the Fermi level: 35 and 55 meV for RT and LT, respectively. This is a consequence of the high DOS value relative to the charge density accumulated at the surface, which requires a limited filling of the low-energy side of the tail (see Fig. 5). The difference between the intensities at RT and LT is due to a different value of the accumulated charge density, 5.2 and 2.3×10^{12} cm^{-2}, respectively, corresponding to a 20-meV lowering of the Fermi level with respect to the subband minimum. The lower accumulation detected at LT is attributed to the decay that the *F* peak has shown as a function of time, probably due to the extreme sensitivity to the contamination from the residual atmosphere.

It is worth noting that actually more than one subband is occupied. This is due to the large width of the DOS compared to both the subband separation [about 30 meV (Ref. 1)] and the k_BT value. However, for the same reason, the above results and discussion keep their validity, because in this case close multiple subbands behave like a single one in determining the DOS shape. As a matter of fact, we expect to resolve each subband contribution if their intensities are similar and their energy separation is large enough compared with their width. However, this hypothesis is never verified, because the thermal distribution leads to the vanishing of all contributions except one if subbands are separated enough to be resolved. Conversely, when subbands are close enough to keep a comparable intensity, their contributions cannot be resolved. This conclusion is confirmed by the application of the fitting model extended to include several subbands, which provides the same results for E_0 and γ obtained in the hypothesis that a single subband was occupied.

The low-temperature deposition of a small quantity of alkali metal on the hydrogenated Si surface results in a noticeably higher value of the band bending (compared to the same deposition at RT) corresponding to a giant emission at the Fermi level (Fig. 4, curve c). On the contrary, the cooling of a surface previously exposed at RT at about the same AM dose leaves the VB spectrum practically unchanged, pointing out a strong Fermi-level pinning at the surface. These results indicate that the large bending induced by the deposition of the alkali metal performed at low temperature is not due to the low temperature itself, but to the different growth conditions. The AM bonding at low temperature seems to be characterized by a much higher charge transfer than that occurring at room temperature, probably due to a temperature dependence of the AM morphology.

At LT, the *F* peak keeps essentially the same shape seen in the case of RT deposition, apart from a small additional structure on the low-energy side. Also in this case we could reproduce the main *F*-peak feature, as shown in Fig. 6, where the calculated spectrum is superimposed to the measured one (dots). In this case the Fermi-level position is different because the measurements have been made with a different (higher) pass energy. By using the same functional form used before, we obtained the best fit corresponding to an accumulation charge density of 4×10^{13} cm^{-2}, and a random-field strength $\gamma=52$ meV. At variance with dosing at AM at RT, the high density of accumulated charge requires that E_0 lie below the Fermi level (40 meV). The charge-density value is just one order-of-magnitude higher than that found in the RT deposition, in agreement with the corresponding *F*-peak intensity ratio, while the strength of the random field γ is about half the value found in the RT deposition. A possible explanation could come from the full quantum treatment of deep tails, where it is shown that the DOS broadening decreases with the increase of the kinetic energy of the 2DEG electrons.[16]

V. CONCLUSIONS

We have shown that the submonolayer deposition of an alkali metal onto the hydrogen-passivated Si(111) surface induces the formation of a two-dimensional electron gas. At variance with other passivated silicon surfaces, this 2DEG derives from the quantization and filling of bulk states located around the conduction-band minimum. Direct photoemission from the accumulation region is found to be well defined and structureless. Its intensity, and the corresponding accumulated charge density, becomes huge when the AM is deposited at low temperature (150 K), indicating a much higher charge transfer in these conditions, probably related to a different growth morphology. The shape of this feature is characterized by a tail which is attributed to the broadening of the density of states induced by the random fields generated by the alkali-metal atoms at the surface, providing direct experimental evidence for the tailing of two-dimensional subbands due to random fields.

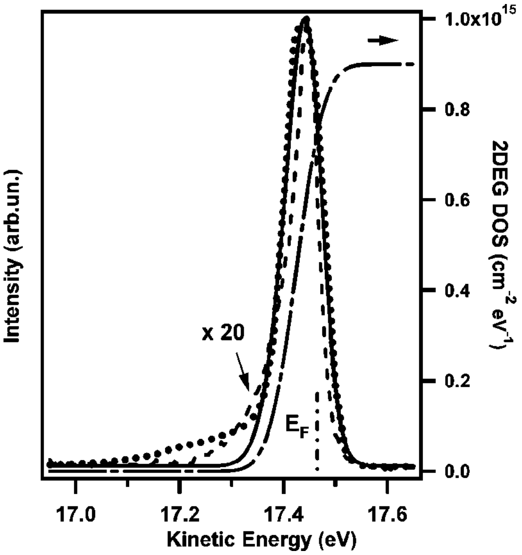

FIG. 6. The Fermi-level peak induced by dosing potassium ($\Theta=0.1$) at LT. Experimental (dots) and calculated (solid) spectra result from the fit based on the density-of-states profile expected for a 2DEG subject to random potentials (long dashes). For comparison, the *F* peak corresponding to the RT deposition measured at LT has been reported (short dashes) multiplied by a factor of 20. The fit corresponds to an accumulated charge density of $4.1\times10^{1}3$ cm^{-2}.

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