Controlling the screening process of a nanoscaled space charge region by minority carriers

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The miniaturization of future electronic devices is intimately connected to the ability to control electric fields on the atomic scale. In a nanoscopic system defined by a limited number of charges, the combined dynamics of bound and free charges become important. Here we present a model system based on the electrostatic interaction between a metallic tip of a scanning tunnelling microscope and a GaAs(110) semiconductor surface. The system is driven out of equilibrium by optical excitation, which provides ambipolar free charge carriers, and by an optically induced unipolar tunnel current. This combination enables the active control of the density and spatial distribution of free and bound charge in the space-charge region, that is, modifying the screening processes. Temporal fluctuations of single dopants are modified, meaning we are able to control the noise of the system. It is found that free charge carriers suppress the noise level in field-controlled, nanoscopic systems.

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Nowadays, semiconductor-based electronic devices have already reached the nanometre size\textsuperscript{1-3}. At this scale, the discreteness of charge, given by, for example, charged single impurities, has already become visible\textsuperscript{4,5}. The latter are the natural limit of the miniaturization process of future electronic applications. Processes, which define the equilibrium charge state of such a nanoscopic device, are shown in Fig. 1a. A gate voltage ionizes dopant atoms to build up the local space charge region (SCR). A current of free minority charge carriers \( I_\text{H} \) towards the field region sets in (Fig. 1a, \( \alpha \)). Recombination of carriers inside the SCR results in spatial and temporal fluctuating charges. All this depends on the charge density, the emission (Fig. 1a, \( \beta \)) and capture rate (Fig. 1a, \( \delta \)) of dopants and the dynamics of the minority charge carriers.

In the following, we describe an approach in which the sharp tip of a scanning tunnelling microscope (STM) serves as the very local gate\textsuperscript{6-10}. Free charge generation by optical excitation and carrier injection by the tunnel current allows driving the system out of equilibrium. We are able to actively control the charge configuration at the surface and thereby establish different screening processes. Values like the carrier flow inside the SCR for different tunnel currents, optical excitation powers and bias voltages can be extracted. Moreover, it is possible to characterize the charge dynamics using a noise analysis of the tunnel current for different charge configurations at the surface.

Figure 1 | Charge dynamics inside a localized space charge region (SCR).

(a) The geometry and spatial extent of a SCR is very sensitive to the charge distribution. Besides ionized dopants, a current of minority charge carriers \( I_\text{H} \) towards the surface is found (\( \alpha \)). This charge replaces the function of the ionized dopants. Doping atoms charge (\( \beta \)) and discharge (\( \delta \)) by capturing free holes or electrons depending on the hole density at the surface. (b) The STM tip-induced potential is used as a local gate electrode to create a SCR of ionized dopants reaching several nanometres into the sample. (c) By generating photoexcited electrons and holes, the free charge is separated by the tip-induced field resulting in a hole accumulation at the surface and thereby to a more efficient screening of the potential drop. (d) Tunnelling electrons address the hole gas, driving the system out of its equilibrium state. By changing the tunnel current, the hole density and, thus, the screening length of the SCR is controlled.

Results
STM on the GaAs(110) surface under optical excitation. Positioned only a few Ångstrom above a surface with a low carrier density, the metallic tip induces a nanoscopic SCR inside the sample (Fig. 1b). At an \( n \)-doped \((3 \times 10^{18} \text{ cm}^{-3})\) GaAs(110) surface with a positive sample voltage of 2.5 V applied, a depletion charge layer is induced extending \( \sim 20 \text{ nm} \) into the sample surface with only \( \sim 10 \) ionized dopants involved\textsuperscript{10}.

To get access to the dynamics of this nanoscaled system, we have combined STM with optical excitation (Fig. 1c). Photo-generated electron–hole pairs will be separated by the electric field. In equilibrium, this current of positive minority charge carriers \( I_\text{H} \) (\( n \)-doped) towards the surface is balanced by recombination and thermionic emission. The SCR is modified by the hole accumulation, screening the potential between tip and sample more efficiently. Originally ionized dopants partly discharge, which results in a shift of the surface potential, by default described as a surface photovoltage\textsuperscript{11}.

The photogenerated charge accumulation at the surface results in an additional current channel\textsuperscript{12-15}. Carrier injection via the tunnel current \( I_\text{T} \) into the valence band distorts the balance of free charge given by optical excitation and locally fixed charge of ionized dopants inside the SCR (Fig. 1d), modifying the non-equilibrium conditions. Surprisingly within the framework of locally resolved surface photovoltage experiments, this carrier injection has been widely neglected up to now\textsuperscript{16-18}. The influence of \( I_\text{T} \) on the screening process of the SCR has been subject to studies before\textsuperscript{13,19-21}. Cahill \textit{et al.}\textsuperscript{19} describes this effect as a consequence of a ‘charging’ due to high tunnel currents leading to an electron accumulation at the surface and counteracting the photogenerated holes. Similar observations were made by Terada \textit{et al.}\textsuperscript{21} discussed as an increase of hole recombination at increased tunnel currents. Chen \textit{et al.}\textsuperscript{20} describe the change in the SCR as a result of a leakage current modifying the concentration of the free, photogenerated charge and is treated as a parasitic side effect. More sophisticated is the work of Sommerhalter \textit{et al.}\textsuperscript{13}. By observing direct tunnelling into minority carriers, they succeeded to develop a model considering the influence of the charge injection by \( I_\text{T} \).

In our experiment, \( I_\text{T} \) is used as a control parameter for the charge distribution inside the SCR. Unlike previous studies, we keep the tip–sample potential constant when changing the tunnel current. This allows us to study the balance of free and bound charge at the surface by actively tuning the screening process of the SCR and to disentangle and control the dynamics of the system by only changing \( I_\text{T} \). At weak photoillumination, we are able to investigate the full range of carrier injection going from low to high currents and thereby at the same time testing and modifying the screening process in three regimes.

Valence band tunnelling visible in STM topographies. In Fig. 2a,b constant current topographies of the optically excited GaAs(110) for positive bias voltages visualize the contribution of tunnelling into photogenerated minority carriers for the first time locally resolved. Different atomic corrugations are observed, which can be attributed to specific resonant surface states positioned energetically inside the valence band (Fig. 2a) and conduction band (Fig. 2b)\textsuperscript{22,23} (Supplementary Note 1; Supplementary Fig. 1). The visibility of the valence band corrugation (Fig. 2a) at positive bias voltage is, in contrast to spectroscopic measurements, a direct evidence that tunnelling into photogenerated holes via valence band tunnelling \( I_\text{T} \) is possible. Under dark conditions at 0.3 V bias voltage, the conduction band cannot be addressed due to the tip-induced band bending. With optical excitation, it is \textit{a priori} open which
tunnel channel (valence or conduction band) is dominant and depends strongly on the density of states and the transmission probability (for details see Supplementary Note 2).

Accessing different tunneling regimes with $I(z)$ spectroscopy. Using $I(z)$ spectroscopy as a function of low optical excitation power $P_L$ and at fixed bias voltage, we are able to exclusively monitor the influence of $I_T$ on the screening process inside the surface. The change in the surface potential when decreasing the tip–sample distance by 3 Å is about 5% of the whole SCR and hence is negligible. Figure 2c–e shows a set of $I(z)$ curves taken at a set point of 2.5 V and 10 pA. It is important to note that this set point allows to directly compare the curves acquired at different $P_L$ (Supplementary Note 1; Supplementary Fig. 2). A plateau-like signature can be identified in the experimental data, moving in
position when changing $P_l$ and bias voltage (the latter not shown here). In standard tunnel theory, the current dependency $I(z)$ on the tip–sample distance $z$ is described by an exponential relation $I(z) \propto \exp(-az)$ with $a = \frac{\Phi}{\kappa}$ and $\Phi$ as the apparent barrier height of the tunnel junction. A closer look on the $I(z)$ spectra in Fig. 2c–e strongly suggests to divide the curve into three electronic configurations, indicated by the blue shadings in Fig. 2c–e and labelled as I, II and III. In I and III, the $I(z)$ curves follow the expected exponential dependency. We extract a barrier height $\Phi$ for the tunnelling electrons of 2.5 eV (see Supplementary Note 3 and Supplementary Fig. 3 for more details), the same value obtained for the $I(z)$ characteristics under dark conditions (dotted line in Fig. 2c). Analogous to the topographic analysis, we conclude that conduction band tunnelling is the predominant process at higher bias voltages. Nevertheless, the topography in Fig. 2a demonstrates that the tunnelling into photogenerated holes is possible.

Modelling the tunnelling into photogenerated minority carriers.

To describe the complex $I(z)$ characteristics under optical excitation, we present a two-channel tunnelling model (Fig. 2g–i), which includes both the current into the valence band $I_V$ and into the conduction band $I_C$.

In regime I (Fig. 2e), the valence band tunnelling $I_V$ is as low that it is not significantly influencing the charge density $n_{\text{H}}$ at the surface. The electrostatic potential between tip and sample is completely screened by the photogenerated charge, leading to flat band conditions for all optical power ratings $P_l$. The tunnelling into the valence band $I_V$ is balanced by a hole current $I_{\text{HF}}^{\text{H}}$. This current can be regarded as a field-driven current induced by the distortion of the hole gas-screening process (hole gas-induced field (HF), see Supplementary Note 4 and Supplementary Fig. 4).

In this regime, the transmission probability and not the density of final states of the tunnelling process is the limiting factor for valence band tunnelling $I_V$. Therefore, $n_{\text{H}}$ defined by the potential between tip and sample and also the SCR is constant as a function of the tunnel current $I_V$.

For higher currents, $I_V$ overcomes $I_{\text{HF}}^{\text{H}}$, resulting in a filling of final states for tunnelling electrons. Consequently, the hole concentration at the surface decreases (Fig. 2h). At the crossover from I to II (at $z_1$), valence band tunnelling $I_V$ and the hole current $I_{\text{HF}}^{\text{H}}$ have equalized. In this transition regime II, the hole density $n_{\text{H}}$ can be actively tuned by adjusting the tunnel current. As this value defines the screening length of the induced field, the $I(z)$ behaviour of the tunnelling into photogenerated minority carriers, giving the position of the plateau region in the $I(z)$ curves, simultaneously. Also, by having a defined SCR in regime I (flat band conditions) and III (TIBB under dark conditions), an extensive computational effort of the tip-induced potential can be avoided.

Noise analysis of the nanoscaled space charge region.

Concluding, it is obvious that different charge configurations have to be considered in the discussed three regimes. To extract the corresponding dynamic properties, we analyse the noise characteristics of the tunnel current. By subtracting a low-frequency filtered $I(z)$ curve from the raw data, the signal in a frequency range between 10 Hz and 1.5 kHz is isolated (Fig. 3a).
In comparison to the noise without optical excitation, we observe a spontaneous increase in noise in regime II in spectra taken at the photoexcited surface. The standard deviation $\sigma_{\text{RMS}}$ in current is plotted against the average current for an optical excitation of 37, 75 and 134 $\mu$W compared to the values under dark conditions in Fig. 3b–d. The behaviour of the noise level in the excited case is unequivocally connected to the previously discussed tunnelling regimes, indicated by the blue shadings in Fig. 3b–d.

At 37 $\mu$W optical excitation (Fig. 3b), the noise in the tunnel regime I shows the same trend compared to the non-excited case. For regime II, $\sigma_{\text{RMS}}$ increases. We attribute this to a non-equilibrium charging and discharging process of dopants$^{5,27}$ inside the SCR (Fig. 1a,d) due to the carrier injection. By disturbing the hole density at the surface by valence band tunnelling $I_V$ drives the SCR in metastable configurations. We expect subtle but frequent changes in the geometry of the SCR leading to variations in the tunnelling current, and thereby to additional noise.

In regime III, we observe a saturation of $\sigma_{\text{RMS}}$, yielding $\sigma_{\text{RMS}}$ (37 $\mu$W) $\sim$ $\sigma_{\text{RMS}}$ (0). Previous studies$^{5,27}$ have shown that under dark conditions bistable charging processes of doping atoms have to be taken into account. Assuming that these processes define the noise level of the spectra without optical excitation, our results suggest that the presence of free electron–hole pairs suppresses this charge switching in the photoexcited case$^{5,27}$. We like to point out that the decrease in noise in comparison to the noise under dark conditions is not the result of a simple decrease of the SCR. Our analysis suggests that in regime III the SCR, normally found under dark conditions, has been rebuilt. Here the charge of the SCR is solely defined by ionized dopants. But even though no more hole accumulation is expected at the surface in the tip-induced field, it is conceivable that the electron–hole pairs, present in the bulk material, cause an additional screening of the SCR. The geometry of the SCR, normally given by the rather stochastic distribution of donors, is smoothed and thereby the charge state of the dopants is stabilized.

By analysing the evolution of the noise level for higher optical power steps at 74 $\mu$W (Fig. 3c) and 134 $\mu$W (Fig. 3d), this free charge stabilization in the bulk material can actually reduce the noise induced by space charge dynamics even in I and II. In this $z$-range, $\sigma_{\text{RMS}}$ decreases monotonically for increasing $P_L$. In particular for an optical power of 134 $\mu$W (Fig. 3d), the noise level is below the values without optical excitation showing that charge switching of bistable dopants is reduced.

From previous studies, the noise level is expected to increase linearly with the tunnel current up to a tunnelling regime close to the point contact of the STM tip$^{28}$. In contrast, in regime III, a saturation in $I_g$ of $\sigma_{\text{RMS}}$ can be observed (Fig. 3b–d), indicating that the resulting $\sigma_{\text{RMS}}$ is defined by processes independent of the tunnel current for the optically excited surface. Regarding the dependency on the optical excitation power, we observe a slight increase of $\sigma_{\text{RMS}}$ with increasing $P_L$. Nevertheless, the saturation behaviour for increasing tunnel currents implies that in the frequency range up to 1 kHz charge fluctuations are the dominant contributions to the noise characteristic.

Discussion

In summary, our results show that tunnelling into minority charge carriers at the surface allows to actively tune the screening process and thereby to decouple the SCR from parameters such as the gate voltage or gate geometry. By controlling the density of minority charge carriers, we are able to suppress the noise in this field determined, nanoscopic system considerably.

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**Figure 3 | Noise analysis of the $I(z)$ spectra.** (a) Current fluctuations of the $I(z)$ spectra (set point: 2.5 V and 10 pA) plotted against the tunnel current without (black), 37 (red), 75 (green) and 134 $\mu$W (yellow) optical excitation. The data sets are displaced vertically. (b–d) Noise level $\sigma_{\text{RMS}}$, plotted against tunnel current.
For a more detailed analysis of the dynamics, a resolution beyond the kHz bandwidth of the STM is required. This can be achieved using pulsed optical excitation, which gives the possibility to gain deeper insight into the time scales of the interplay of the tunnel current $I_T$ and the minority carrier current $I_m$.

**Methods**

**Experimental set-up.** The experiments are performed in a custom-built, low-temperature STM working under UHV condition (6 k at a base pressure of $P < 3 \times 10^{-11}$ mbar). For optical excitation, a stabilized continuous wave diode laser at a wavelength of 785 nm and a maximum power of 100 mW is used. The focus diameter of this laser is about 30 μm. With an illumination angle of roughly 30° this results in an optical excited area of 1.57 $\times$ 10$^{-9}$ m$^2$. The tips are electrochemically etched from a polycrystalline tungsten wire. The typical tip radius is about 10–40 nm. I(V,t) spectroscopy is used to study the effect of the tunnelling process on the photogenerated charge.

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**Author contributions**

M.W. and P.K. planned the experiment. P.K. and K.K. conducted the experiment and the data analysis. P.K. and M.W. wrote the manuscript. All authors discussed the results and commented on the manuscript.

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