Supporting information:

Fast hole tunneling times in Germanium hut wires probed by single-shot reflectometry

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Discussion of the effect of the finite rise time of the low pass filter on the extracted tunneling times

We made a simple simulation of our experiment which explains the possibility to measure tunnel events on a microsecond time scale even if the low pass filter rise time is several times longer. The setup of the simulated experiment is shown in Figure S1.

A square waveform 1 with the amplitude of 0.2 mV was generated and sent out from the 1st channel of the arbitrary wave generator (AWG5014C); it corresponds to the pulse applied in order to load a hole inside the QD. A similar square waveform was generated from the second channel of the AWG5014C, with delay times of 5 µs and 7 µs and is used to simulate the response of the sensor after a hole has tunneled into the QD. This second waveform was fed to the IF port of a RF mixer. A sinusoidal carrier signal of 100 MHz
was generated from the UHFLI *out 1* port and fed to the *LO* port of the mixer in order to imitate the reflectometry signal. The result of the multiplication of these two signals, was fed to the UHFLI *input 2* from the mixer *RF* port and measured with its scope (see Figure S1). The scope sampling rate was set to 900 MHz. To observe the influence of the UHFLI demodulator, the signal was fed through it with a low pass filter of 20 kHz (4th order) (Figure S2 c) and d)). The threshold for the 'tunnel time measurement' for this simulation was set to 100 mV. We can see that an additional delay of 15 µs, originating from the slow rise time, is added for both the left (5 µs) and the right (7 µs) tunnel event equally, proving that the filter behavior is constant and simply adds a constant offset in the measurement. However, due to the fact that the pulse duration, marked as L, in the experiment described in Figure 4 of our manuscript is more than 30 times the rise time, all tunneling events are observed. Note: The amplitudes of all measurement simulations shown here are 5-6 orders of magnitude higher than in the real experiment. The reason for this is that for the proper operation of the mixer, the signal amplitudes on it’s inputs need to have certain value.

We have repeated the same simulation for 30 kHz, 50 kHz and 100 kHz low pass filter bandwidths and the final difference between the two signals simulating the tunneling events was always 2 µs (see Figure S3), as it would be for an infinite bandwidth setup.
Figure S2: Measurements of the simulated experiment proving the validity of our experimental approach. a) In blue the square waveform corresponding to the pulse for loading a hole is shown. The second square waveform, multiplied with a 100 MHz sinusoidal signal, simulating the tunneling event is shown in green. The high level of this second waveform is delayed for 5 µs simulating the time it takes for a hole to tunnel into the QD after the blue square waveform has been applied. b) Similar to a) but here, the second waveform is delayed for 7 µs. In the inset a zoom-in of the 'reflectometry carrier signal' of 100 MHz modulated with the square waveform, is shown. c) - d) Demodulated signal measured after the low pass filter of 20 kHz (4th order), simulating tunnel events which take place after delay times of 5 µs and 7 µs, respectively. The simulation reveals that the slow rise time adds an additional delay time of 15 µs for both tunnel events.
Summarizing, the low-pass filter bandwidth does not influence our measurement, since we measure only the relative delay. The consequence of measuring with a smaller bandwidth is just a shift of the whole histogram on the x-axis. The shift of the fitted histograms is inversely proportional to the low-pass filter bandwidth: the higher the bandwidth, the closer to zero time is the histogram. The histograms shift to smaller delay times for higher bandwidth but the extracted tunneling times are the same. This can be seen in Figure 4 of the manuscript.
Figure S3: Simulated total delay times (tunneling time + rise time of the low pass filter) for (a)-(b) 30 kHz, (c)-(d) 50 kHz and (e)-(f) 100 kHz bandwidths, for two tunneling events. The square waveform corresponding to the pulse for loading/unloading the hole is shown in blue. The demodulated signal simulating the tunnel events after 5 $\mu$s (left) and 7 $\mu$s (right) is shown in green.