Observation of decoupling of electrons from phonon bath close to a correlation driven metal-insulator transition

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Abstract

We observed that close to a Mott transition, over a small temperature range, the predominance of slow relaxations leads to decoupling of electrons from the thermal bath. This has been established by observation of large deviation of white thermal noise in the films of Mott system NdNiO₃ from the canonical Johnson-Nyquist value of $4k_B T R$ close to the transition. Evidences obtained through spatially resolved scanning tunneling conductance map and correlation function of fluctuations suggest that rare small pockets of metallic phases within the insulating phase can lead to such a phenomenon.

Key words: Metal insulator Transition, Mott Transition, Disorder, Slow Relaxation, Johnson-Nyquist thermal noise
Metal-Insulator Transition (MIT), where a metal with delocalized electrons makes a transition to an insulating state with strongly localized electrons, is one of the most fascinating areas of research in modern condensed matter physics. Despite seminal contributions that enriched this field, there are fundamental unresolved issues that need attention. The most attractive feature of MIT is that it is a general phenomenon observed in a number of systems and despite the differences, there are certain attributes that have a ubiquitous presence in the physics of MIT.

In recent years a number of new exciting issues have been brought forward, like the slowing down of charge relaxation close to MIT. Observation of critical slowing down has been observed through Noise measurements$^1$ as well as in NMR relaxation time measurements$^{2,3}$ in polymeric/organic conductors with disorder undergoing Mott transition. The emergence of such slow relaxation close to Mott Transition with the disorder has been suggested as a manifestation of electronic Griffiths phase$^{3,4,5}$. Critical slowing down and enhanced order parameter fluctuations have been observed near the Mott transition in $V_2O_3$.$^6$

The field of MIT developed along with two directions. One direction is the disorder driven Anderson transition$^{7,8,9}$ where the density of states (DOS) at the Fermi level $N(E_F)$ remains finite ($N(E_F) \neq 0$) although with localized electronic states around $E_F$. Presence of long-range coulomb interaction leads to opening of a soft-gap at $E_F$.$^1^0$. The other is the correlation driven Mott transition$^{1^1,1^2}$ where the DOS at $E_F$ splits into two bands with $N(E_F) \to 0$ at the transition. In recent years there is a convergence of the two broad classes of MIT which is referred as the Mott-Anderson transition where there is a presence of both disorder and correlation$^{1^3,1^4}$. The present report is placed in this contextual framework.
The thermodynamics of MIT has important physical consequences. The Anderson transition is a continuous transition where conductance \( G \) plays the role of an order parameter\(^9\). The Mott transition is generally thought of as 1\(^{st}\) order transition which can be broadened by disorder\(^1\text{-}^3\).

In MIT, like in any other phase transition, one would expect divergence of correlation length and critical slowing down close to critical region. In the context of Anderson transition, such slowing down and the emergence of very low-frequency charge relaxation have been observed as \( T \to 0 \) through resistance/conductance noise measurement in 2-dimensional systems like MOSFET\(^{15}\) and in 3-dimensional system Si (P, B)\(^{16}\). The emergence of slow relaxation in the transition region of Mott transition \(^1\text{-}^3,^6\), are finite temperature analogues of the zero temperature phenomena observed near \( T \to 0 \) in Anderson transition.

In this paper, we report on a fundamental aspect of the temperature driven Mott transition that has not been reported before. We investigate thermodynamic consequences of slowing down of relaxation as a precursor of MIT. We find in a narrow temperature range close to the Mott transition temperature \( (T_{MI}) \), the electron system loses equilibrium with the thermal bath formed by the phonons. This has been established through the observation of a large spectral power density of the Johnson-Nyquist (JN) thermal noise\(^{17,18}\) close to \( T_{MI} \) in films of NdNiO\(_3\) grown on different crystalline substrates. NdNiO\(_3\) (NNO) undergoes temperature-driven Mott type MIT that has attracted considerable attention in recent years\(^{19,20}\). The transition in NNO, as reported recently, shows co-existence of insulating and metallic phases\(^21\). Though investigated on rare-earth nickelate NdNiO\(_3\), the reported phenomenon as described is of general validity and is expected to be observed in any Mott transition.

Thermal noise is a consequence of the Fluctuation Dissipation Theorem (FDT)\(^{22}\) and shows up as a voltage fluctuation (without an applied bias) across a dissipative circuit element like a resistor \( R \) kept at a bath temperature \( T \). The mean square voltage fluctuation \( \langle (\delta V)^2 \rangle \) measured over a bandwidth \( \Delta f \) is given by the relation\(^{18}\):
\[
\langle (\delta V)^2 \rangle = (4k_BRT)\Delta f \tag{1}
\]

For Eqn. 1 it is assumed that the electron system, with characteristic effective temperature \( T_e \) is in equilibrium with the phonon thermal bath at temperature \( T \) so that \( T_e = T \). The fluctuation gives a fundamental measurement of the bath temperature \( T \) and forms the basis of noise thermometry in metrology\(^2\). Thermal noise is a white noise with frequency-independent spectral power density given as\(^1\):

\[ S_{th} = 4k_BRT \tag{2} \]

Eqn. 2 is applied to measure the electron temperature \( T_e \) in a hot electron system like in a solid-state electronic device where \( T_e > T \)\(^2\). In such a system measured thermal noise \( S_{th} > 4k_BRT \).

The NNO films of thickness nearly 15nm and root mean square (RMS) roughness of 0.3nm used in the experiment were grown on crystalline substrates like SrTiO\(_3\) (STO) with surfaces of different crystallographic orientations and on NdGaO\(_3\) (NGO) and LaAlO\(_3\) (LAO) by Pulsed Laser Deposition (PLD) using a KrF (\( \lambda = 248\text{nm} \)) laser. Some of the details of growth and characterization of the films are given in previous publication from the group\(^2\). The films are strain relaxed as established by the reciprocal space mapping (RSM) using X-Ray. This gives rise to disorder in the films. (RSM data in Supplementary Information. Figures S13-S15 and Table SI)

The resistivity (\( \rho \)) was measured down to 3K in a collinear 4-probe configuration. The noise measurements (for 80K < \( T < 300K \)) were performed using a 5-probe a.c. excitation\(^2\) technique using temperature stabilization of \( \pm 5 \) mK. The method allows simultaneous
measurements of the flicker noise (spectral power density $S_V(f) \propto \frac{1}{f^\nu}$) as well as the frequency-independent thermal noise $S_{th}$. The details are given elsewhere\textsuperscript{26,27}. In general, a number of extraneous noise sources can add to the observed $S_{th}$ and can make the observed $S_{th}$ deviate from the value given by Eqn. 2. However, proper elimination of these factors can bring down observed $S_{th}$ close to the canonical value within a factor of 1.5 or even better. The noise floor measurable in our set-up is $2 \times 10^{-20}$ V$^2$/Hz established by measurement on a standard resistor.

In Figure 1 we show an example of the noise spectroscopy data taken on a film of NNO grown on STO with (111) orientation (NNO/STO (111)). It shows the frequency-independent thermal noise $S_{th}$ along with the flicker noise with spectral power $S_V(f) \propto \frac{1}{f^\nu}$. The inset the $\rho$ vs $T$ data of the film. $T_{MI}$ is determined by change in the sign of the temperature derivative $\frac{d\rho}{dT}$ and also marked in the figure.

**Figure 1:** Example of measured Spectral power density ($S_V(f)$) for the flicker noise varying as $\frac{1}{f^\nu}$ and measured thermal noise $S_{th}$ (white spectrum) in a NNO/STO (111) film. The Nyquist- Johnson value of $S_{th} = 4k_B T R$ for the resistance at 270K is marked by an arrow. Inset : resistivity of the film NNO/STO (111).
Data for NNO films grown on STO with different orientations are summarized in Table I. Resistivity data for the other films measured are given in Supplementary Information Figure S1 and S2.

| Sample            | $\epsilon_\perp$ (%) | $\epsilon_\parallel$ (%) | $T_{MI}$ (K) | $T^*$ (K) | $T^*/T_{MI}$ | $\zeta_M$ |
|-------------------|-----------------------|---------------------------|--------------|-----------|--------------|-----------|
|                   | H         | C         | H         | C         | H         | C         | H         | C         |
| NNO/STO(100)      | -0.081    | 0.094     | 181       | 159       | 160       | 142       | 0.88      | 0.89      | 10         | 4         |
| NNO/STO(110)      | 0.015     | -0.017    | 216       | 198       | 200       | 182       | 0.93      | 0.92      | 11         | 7         |
| NNO/STO(111)      | 0.359     | -0.419    | 215       | 182       | 228       | 202       | 1.06      | 1.11      | 12         | 10        |

# : Out-of-plane strain (c-axis) $\epsilon_\perp = \frac{c_{film} - c_{film}}{c_{substrate}}$, S: In-plane strain (a-axis) $\epsilon_\parallel = \frac{a_{film} - a_{film}}{a_{substrate}}$ as determined from X-ray data. Subscripts film and substrate refer to the film and the substrate respectively. The super-script R refers to the fully relaxed film. H = Heating cycle, C = Cooling Cycle, $T_{MI}$ = MI transition temperature, $T^*$ = Temperature at which thermal noise ($S_{th}$) shows a peak. $\zeta_M$ is the peak value of the ratio $\zeta = \frac{S_{th}(T)}{4k_BT^*}$ observed at $T^*$.

Figure 2 shows the temperature variation of the exponent $\alpha$ for the spectral power density of the flicker noise $S_V \sim \frac{1}{f^{\alpha}}$ for the film NNO/STO (111) for both heating and cooling cycles. It can be seen that around a narrow temperature range close to $T_{MI}$, $\alpha$ deviates significantly from the expected value of $\alpha \approx 1.0 \pm 0.1$. Figure 2 inset shows the relative variance of the resistance fluctuation ($\frac{(\Delta R^2)}{R^2}$), which is the magnitude of the fluctuation. \[ \frac{(\Delta R^2)}{R^2} = \int_{f_{\min}}^{f_{\max}} df \left( \frac{S_V(f)}{V^2} \right) \] evaluated over the bandwidth of the measurement ($f_{\max}, f_{\min}$)]. The peaks in $\alpha$ as well as in $\frac{(\Delta R^2)}{R^2}$ occur at the same temperature and in a narrow temperature range close to $T_{MI}$. This would imply that there is a predominance of slow relaxations that add to the spectral weights at low frequency thus enhancing $\alpha$.  


Figure 2. Temperature variation of the exponent $\alpha$ for the Flicker noise, $S_v \sim \frac{1}{f^\alpha}$, for NNO/STO (111) film. Inset: Relative variance $\frac{\langle \Delta R^2 \rangle}{R^2} = \int_{f_{min}}^{f_{max}} df \frac{S_v(f)}{\sqrt{V}}$. The arrows mark the temperature where $\alpha$ and the variance show peaks. Data for other films are given in supplementary information Figures S3 and S4.

In Figure 3 shows $\zeta \equiv \frac{S_{th}(T)}{4k_BTR}$ which is the measured thermal noise $S_{th}(T)$, scaled by canonical Johnson Nyquist (JN) value $4k_BTR$ for the resistance value $R$ for the NNO films. This is the most important result which shows the decoupling of the electrons from the lattice thermal bath. For a system in thermal equilibrium, $\zeta \approx 1$. We find that in a narrow temperature range close $T_{M1}$ in all the films studied $\zeta$ values are substantially $\gg 1$. The temperature at which $\zeta$ reaches a peak value of $\zeta_M$ we call it $T^*$. For the heating cycle for all the film $\zeta_M \geq 10$ and during the cooling cycle $\zeta_M \geq 4$. (see Table I). Importantly, $T^*$ coincides with the temperatures where one observes the concomitant jumps in the exponent $\alpha$ and in $\frac{\langle \Delta R^2 \rangle}{R^2}$ for all the films studied. Thus over a narrow temperature range around $T^*$ the predominance of slow relaxations as observed by the noise spectroscopy leads to a deviation of thermal noise from the canonical JN value signifying that the electrons loose equilibrium to the thermal bath of phonons as a consequence of the slow relaxation.
Figure 3. The temperature dependence of $\zeta (\equiv \frac{S_{th}(T)}{4k_BT_R})$ for NNO films grown on STO substrates with different orientations. Data are shown for the heating cycle. The arrows mark $T^*$. For the cooling cycle and other films in Supplementary Figures S5 and S6.

The ratio $\frac{T^*}{T_{MI}}$ as well as $\zeta_M$ depend on the extent of the in-plane strain ($\epsilon_\parallel$) in the film as measured by X-ray (For strain data see Supplementary Information Table SI). Data are shown in Figure 4 and the inset (see also Table I). Both the extent of the decoupling (measured by $\zeta_M$) as well as the ratio $\frac{T^*}{T_{MI}}$ increase as $\epsilon_\parallel$ increases. Even in films with the small strain (~0.1%), there is a substantial departure of $S_{th}$ from the equilibrium value signifying clear thermal decoupling of the electrons from the bath.

Figure 4. Dependence of $\frac{T^*}{T_{MI}}$ on in-plane strain $\epsilon_\parallel$ for films of NNO grown on STO substrates with different orientations. See also table I. Blue and red colors represent cooling and heating cycle data respectively. Inset (top
right): Dependence of \( \zeta_M \) on \( \epsilon_\parallel \). The inset (bottom left): Schematic of coexisting phases with trapped small metallic phase (yellow) in a minority insulating phase.

In Figure 5 we show the autocorrelation function \( C(t) \) of the voltage fluctuations (that gives the flicker noise) at \( T = T^* \). The inset at top right (the correlation time (\( \tau \)) vs. scaled temperature \( \frac{T}{T^*} \)) shows that the large jump \( \zeta \) is correlated with the maxima of \( \tau \) at \( T^* \). This establishes that the decoupling of the electrons with the thermal phonons occur when there is slowing down of the time scales of fluctuation.

At and around \( T^* \), the fluctuation also becomes strongly correlated and develops a component of non-Gaussianity as measured by the normalized second spectrum of the fluctuation (\( \Gamma^2 \)). Data and details are given in Supplementary Information Figures S9-S12.

**Figure 5.** Auto-correlation function \( C(t) \) vs. \( t \) for NNO/STO(111) at \( T = T^* = 228K \) (heating cycle). The line through the data points show the fit to the relation \( C(t) \sim e^{-(\ln (t))^{3/2}} \). Inset (upper right) shows the correlation time \( \tau \) as a function of scaled temperature \( \frac{T}{T^*} \). Cooling cycle and \( \tau \) vs \( \frac{T}{T^*} \) data for other films in supplementary Figures S7 and S8 respectively. Inset (lower left) shows LCMAP of NNO film close to \( T^* \). Color bar to the right.

Previous reports of noise spectroscopy near MI transition in rare-earth nickelates\(^ {21,28-30}\) have reported the emergence of low-frequency correlated fluctuations near the MIT as observed from exponent \( \alpha \), variance \( \frac{(\Delta R^2)}{R^2} \) and second spectra \( \Gamma^2 \). Similar results have also been reported for other temperature-driven MITs in oxides like that in VO\(_2\) \(^ {31}\) and V\(_2\)O\(_3\) \(^ {6}\) and polymeric
However, no report exists that observes a large deviation of the thermal noise from the JN value signifying decoupling of electron bath from the phonon bath, concomitant to the existence of low frequency fluctuations.

It has been suggested that transfer of spectral weight at the Fermi level to and from the Hubbard bands at the MIT can lead to an electronic bottleneck due to slow relaxation resulting in a decoupling of hot electrons from the lattice \(^4\). The observed decoupling of the electrons from the phonon bath does point to such phenomena. We show below that such a process may get accentuated due to the presence of small pockets of metallic phases in the insulating phase.

In the temperature range around \(T^*\) there is co-existence of the insulating and metallic phases as observed by spatially resolved techniques \(^21\). The fractions of co-existing phases have been evaluated from the \(\rho - T\) curves using effective medium theory \(^32\). For \(T \sim T^*\), the insulating phase is the minority phase. While such phase co-existence can enhance the fluctuations (larger \(\langle \Delta R^2 \rangle / R^2 \)), there is no \textit{a priori} reason that this may lead to enhancement of thermal noise. However, if there are small volumes of metallic phases trapped within the minority insulating phase such isolated islands of metallic phases can have nanometric dimensions, which would lead to large fluctuations enhancing both the Flicker noise and the thermal noise. (Schematic of the proposed scenario shown in the lower inset of figure 4.) As \(T\) changes, either these rare regions become bigger (during heating) merging with the majority metallic phase or cease to exist within the insulating phase as the later volume fraction increases on cooling. This explains the rather narrow temperature range around \(T^*\) where it appears.

Such isolated small metallic phase trapped within a minority insulating phase are rare regions that can arise if there is existence of electronic Griffiths phase close to the transition, a scenario proposed for Mott transition with disorder \(^32\). The existence of Griffiths phase has also been proposed as an explanation of slow fluctuations observed near Mott transition in the presence of disorder \(^3\). The suggestion that the observed phenomena can be a manifestation of the
electronic Griffiths phase finds support from the auto correlation function of fluctuation $C(t)$ obtained for the flicker noise data. $C(t)$ shows a departure from normal exponential behavior at or near $T^*$ for large $t$. We find that in this temperature range for large $t$, $C(t) \sim e^{-(\ln(t))^{3/2}}$ as shown by the fitted line in Figure 5. Such an auto correlation function has been proposed for classical models of fluctuation in the Griffiths phase for 3-dimensional systems. We have also been able to generate the local tunneling conductance $g(V)$ map (LCMAP) close to the temperature $T^*$ using an Ultra High Vacuum Scanning Tunneling Microscope. Using Scanning Tunneling Spectroscopy we looked for such rare metallic regions with metallic tunneling conductance which is proportional to the local density of states at $E_F$. (Details in supplementary section). An example of the data is shown in the inset of Figure 5 where it can be seen that close to $T^*$ there are nanometric pockets of larger $g$.

Concluding remarks- We report the first observation of the decoupling of the electron system from the temperature bath formed by the phonons in films of NdNiO$_3$ close to its Mott type MI transition. It has been observed, close to the transition temperature, by direct measurement of the electron effective temperature through measurement of the white thermal noise which shows a large deviation from the canonical Jonson-Nyquist value of $4k_BT_R$. The large rise in the thermal noise occurs due to the predominance of slow relaxations whose presence has been confirmed by a large rise of the correlation time of fluctuations and also concomitant large enhancements in the mean square resistance fluctuation of the flicker noise as well as of the exponent $\alpha$. A scenario has been proposed where it has been suggested that rare small pockets of metallic phases (which otherwise form the majority phase) within the minority insulating phase can lead to such a phenomenon. STM based LCMAP shows existence of such regions.
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References

1. Benedikt Hartmann, David Zielke, Jana Polzin, Takahiko Sasaki, and Jens Müller, Phys. Rev. Lett 114, 216403 (2015)

2. Tetsuaki Itou, Eri Watanabe, Satoru Maegawa, Akiko Tajima, Naoya Tajima, Kazuya Kubo, Reizo Kato, Kazushi Kanoda, Sci. Adv. 3, e160159, (2017)

3. R. Yamamoto, T. Furukawa, K. Miyagawa, T. Sasaki, K. Kanoda, and Tetsuaki Itou, Phys. Rev. Lett 124, 046404 (2020)

4. Sharareh Sayyad and Martin Eckstein, Phys. Rev. Lett 117, 096403 (2016)

5. Thomas Vojta, AIP Conference Proceedings 1550, 188 (2013).

6. Satyaki Kundu, Tapas Bar, Rajesh Kumble Nayak, Bhavtosh Bansal, Phys. Rev. Lett 124, 095703 (2020)

7. P.W. Anderson, Phys. Rev 109, 1492 (1958)

8. Ferdinand Evers and Alexander D. Mirlin, Rev. Mod. Phys. 80, 1355 (2008)

9. Patrick A. Lee and T. V. Ramakrishnan Rev. Mod. Phys. 57, 287 (1985)

10. A.L. Efros, Journal of Physics C: Solid State Physics. 9, 2021 (1976).

11. N.F. Mott, Proc. Phys. Soc. A 62, 416 (1949)

12. Masatoshi Imada, Atsushi Fujimori, and Yoshinori Tokura, Rev. Mod. Phys. 70, 1039 (1998)

13. D. Belitz and T. R. Kirkpatrick, Rev. Mod. Phys. 66, 261 (1994)

14. Zhenyu Wang et.al PNAS. 115, 11198 (2018)

15. S. Bogdanovich and D. Popovic, Phys. Rev. Lett. 88, 236401 (2002).

16. Swastik Kar, A. K. Raychaudhuri, and Arindam Ghosh, H. v. Lo¨hneysen and G.Weiss, Phys.Rev.Lett.91, 216603 (2003)

17. J.B. Johnson Nature 119 50 (1927)

18. H. Nyquist, Phys. Rev. 32, 110 (1928)).

19. S. Middey, J. Chakhalian, P. Mahadevan, J. W. Freeland, A. J.Millis, and D. D. Sarma, Annual. Rev. Mater. Res. 46, 305 (2016).
20. S. Catalano, M. Gibert, J. Fowlie, J. Íñiguez, J. M. Triscone and J. Kreise, Rep. Prog. Phys. 81, 046501 (2018).
21. Ravindra Singh Bisht, Sudeshna Samanta, and A. K. Raychaudhuri, Phys. Rev. B 95, 115147 (2017).
22. H.B. Callen, T.A. Welton, Phys. Rev. 83 34 (1951).
23. S. P. Benz, A. Pollarolo, J. Qu, H. Rogalla, C. Urano, W. L. Tew, P. D. Dresselhaus, and D. R. White, Metrologia 48, 142 (2011).
24. J.-P. Nougier, IEEE Transactions on Electron Devices 41, 2034 (1994), The effective electron temperature $T_e$ is evaluated from the measured spectral power density of the thermal noise $S_{th}$ from the relation: $T_e = \frac{S_{th}}{4k_B R}$
25. J.H. Scofield, Rev. Sci. Instr. 58, 985 (1987).
26. A. K. Raychaudhuri, Curr. Opin. Solid State Mater. Sci. 6, 67 (2002).
27. A. Ghosh, S. Kar, A. Bid, and A. K. Raychaudhuri, arXiv:condmat/0402130v1.
28. A. Sahoo, S. D. Ha, S. Ramanathan, and A. Ghosh, Phys. Rev. B 90, 085116 (2014).
29. A. M. Alsaqqa, S. Singh, S. Middey, M. Kareev, J. Chakhalian, and G. Sambandamurthy, Phys. Rev. B 95, 125132 (2017).
30. Gopi Nath Daptary, Siddharth Kumar, M. Kareev, J. Chakhalian, Aveek Bid, and S. Middey, Phys. Rev. B 100, 125105 (2019).
31. S. Samanta, A. K. Raychaudhuri, X. Zhong, and A. Gupta, Phys. Rev. B 92, 195125 (2015).
32. D.S. McLachlan, J.Phys C: Solid State Phys. 20, 865 (1987).
33. D. Tanaskoviæ, E. Miranda, and V. Dobrosavljevïæ, Phys. Rev. B 70, 205108 (2004)
Supplementary Information

Decoupling of electrons from phonon bath close to a correlation driven metal-insulator transition

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Figure S1. Resistivity (ρ) vs Temperature of NNO/STO(100) and NNO/STO(110) films.

Figure S2. Resistivity (ρ) vs Temperature of NNO/ NGO (100) film. Resistivity data for NNO/LAO (100) in Reference 21.
**Figure S3.** Temperature variation of the exponent $\alpha$ for the spectral power density $S_\nu \sim \frac{1}{f^\alpha}$, for NNO/STO (100) film. Inset: Relative variance $\frac{\langle \Delta R^2 \rangle}{R^2} = \int_{f_{\text{min}}}^{f_{\text{max}}} df \left( \frac{S_\nu(f)}{\nu^2} \right)$. The arrows mark the temperature where $\alpha$ and the variance show peaks.

**Figure S4.** Temperature variation of the exponent $\alpha$ for the spectral power density $S_\nu \sim \frac{1}{f^\alpha}$, for NNO/STO (110) film. Inset: Relative variance $\frac{\langle \Delta R^2 \rangle}{R^2} = \int_{f_{\text{min}}}^{f_{\text{max}}} df \left( \frac{S_\nu(f)}{\nu^2} \right)$. The arrows mark the temperature where $\alpha$ and the variance show peaks.
Figure S5. The temperature dependence of the ratio $\zeta(\equiv \frac{2n_0(T)}{4k_B T R})$ of the observed white thermal noise spectral power $S_{th}(T)$ and the Johnson-Nyquist noise value of $4k_BT R$ for the resistance value $R$ of the sample at the temperature $T$ for NNO films grown on STO substrates with different orientations. Data are shown for the cooling cycle.

Figure S6. The temperature dependence of the ratio $\zeta(\equiv \frac{2n_0(T)}{4k_B T R})$ of the observed white thermal noise spectral power $S_{th}(T)$ and the Johnson-Nyquist noise value of $4k_BT R$ for the resistance value $R$ of the sample at the temperature $T$ for NNO films grown on LAO and NGO substrates. Data are shown for the heating cycle.
Figure S7. Representative the Auto-correlation function $C(t)$ as a function of time (t) for the film NNO/STO(111) for cooling cycle at $T = T^*$. The black line through the data points show the fit to the relation: $C(t) \sim e^{-(\ln(t))^{3/2}}$

Figure S8. Plot of correlation times $\tau$ vs $\frac{T}{T^*}$ for NNO/STO(100) and NNO/STO(110) films for heating and cooling cycle.
Note on 2nd Spectra:

The second spectrum $\Gamma^2$ is defined as $\int_{f_L}^{f_H} S^2(f_2) df_2$ where $S^2(f_2)$ is defined as a normalized second spectrum. The normalization is by the square of the integrated spectral power density (the first spectrum). The definition is given by $^{21,31}$

$$S^2(f_2) = \frac{\int_0^\infty \langle \Delta V(t) \Delta V(t+\tau) \rangle \cos(2\pi f_2 \tau) d\tau}{\left[ \int_{f_L}^{f_H} S_V(f_1) df_1 \right]^2}$$

Where $f_1$ and $f_2$ are the frequencies associated with first and second spectrum respectively. The spectrum has been calculated within the frequency bandwidth of 0.25 Hz, where $f_1$ is 0.25 Hz, $f_L = 0.25$ Hz and $f_H = 0.5$ Hz. For a perfect Gaussian fluctuation, $S^2(f_2) = 3$. The large change in $\Gamma^2$ the second spectrum close to $T_{MI}$ is a signal of correlated non-Gaussian fluctuation.

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**Figure S9.** The second spectrum $\Gamma^2$ of the noise spectra for NNO/STO (111) film with scaled temperature scale $\frac{T}{T^*}$ for heating and cooling cycle.

**Figure S10.** The second spectrum $\Gamma^2$ of the noise spectra for NNO/STO (110) film with a scaled temperature scale $\frac{T}{T^*}$ for heating and cooling cycle.
Figure S11. The second spectrum $\Gamma^2$ of the noise spectra for NNO/STO (100) film with scaled temperature scale $\frac{T}{T^*}$ for heating and cooling cycle.

Figure S12. The second spectrum $\Gamma^2$ of the noise spectra for NNO/NGO (100) film with scaled temperature scale $\frac{T}{T^*}$ for heating cycle. Data for NNO/LAO (100) in Reference 21.

Reciprocal Space Mapping (RSM) data and analysis

Figure S13. RSM data for NNO/STO(100) film measured along (103) reflection.
The x-ray reciprocal space mapping (RSM) measurements are carried out using Bruker D8-Discover system equipped with Cu Kα radiation, Eulerian cradle, Goebel mirror and LynxEye detector. The obtained data is analysed with LEPTOS software considering pseudo-cubic notation for NNO layer (0.3807 nm). Since there is no information about the elastic constants of NNO, the Poisson ratio of 0.3 is considered as adopted from published data (Adam J. Hauser, Evgeny Mikheev, Nelson E. Moreno, Jinwoo Hwang, Jack Y. Zhang, and Susanne Stemmer *Correlation between stoichiometry, strain, and metal-insulator transitions of NdNiO₃ films* Appl. Phys. Lett. 106, 092104 (2015); https://doi.org/10.1063/1.4914002). The
RSM measurements are carried out along both symmetric (002) and asymmetric (103) reflections. The data measured along (103) reflection is shown in Figure-S13, S14, S15. The constructed relaxation triangle (one vertex of the triangle is the substrate peak, the other two vertexes are layer peaks for pseudo-morphic and fully relaxed states) is shown in the figures. The data suggest the fully relaxed states, also reflected in the R (Relax) value. Value more than one could be due to the consideration of approximate elastic constants of the NNO layer. The formulas used for calculating the parameters shown in the table are the following.

**Table SI**

| Sample            | a<sub>Film</sub> (nm) | c<sub>Film</sub> (nm) | Relax (R) | Δa/a (%) | Δc/c (%) | In-plane Strain % (ε∥) | Out of plane Strain % (ε⊥) |
|-------------------|------------------------|------------------------|-----------|----------|----------|-------------------------|---------------------------|
| NNO/STO(100)      | 0.38107                | 0.38038                | 0.96      | -2.415   | -2.592   | 0.094                   | -0.081                    |
| NNO/STO(110)      | 0.38063                | 0.38076                | 1.01      | -2.527   | -2.494   | -0.017                  | 0.015                     |
| NNO/STO(111)      | 0.37906                | 0.38210                | 1.16      | -2.929   | -2.151   | -0.419                  | 0.359                     |

STO (cubic) : a<sub>Sub</sub>c<sub>Sub</sub> = 0.3905 nm

NNO (pseudo-cubic) : a<sub>Film</sub>c<sub>Film</sub> = 0.3807 nm

Δa/a = (a<sub>Film</sub> - a<sub>Sub</sub>) / a<sub>Sub</sub>

Δc/c = (c<sub>Film</sub> - c<sub>Sub</sub>) / c<sub>Sub</sub>

Lateral strain = (a<sub>Film</sub> - a<sub>R Film</sub>) / a<sub>Sub</sub>

Vertical strain = (c<sub>Film</sub> - c<sub>R Film</sub>) / c<sub>Sub</sub>

Relax = (a<sub>Film</sub> - a<sub>Sub</sub>) / (a<sub>R Film</sub> - a<sub>Sub</sub>)

**Note on Local conductance map (LCMAP)**

LCMAP is a spatially resolved image of local tunneling conductance g(V) taken over an aerial range of 0.5μm × 0.5μm using a UHV Scanning Tunneling Microscope (STM) at a fixed bias.
V. The data were taken with STM UHV SPM 350 by RHK technology at a base pressure of $10^{-10}$ mbar. The local tunneling conductance $g(\equiv \frac{dl}{dv})$ that provides the information on spatial dependence of the DOS at the Fermi level ($E_F$) has been measured using a modulation method with a small ac bias that is applied to the dc bias $V$ which is used for keeping a fixed height of the tip above the film. The small a.c modulation voltage ($<<$ the dc bias) that has been used to measure the differential tunneling conductance $\frac{dl}{dv}$. Taking a raster scan in the presence of an ac modulation allows one to record the topography as well as spectroscopy data together. The system has a noise level $\leq 10 \text{ pA/Hz}$. The local tunneling conductance map is a contour plot of $g = \frac{dl}{dv}$ taken at a fixed dc bias $V=0.5V$. The color code gives the corresponding value of $g(V)$ with regions of higher tunneling conductance being metallic regions.