

A Heteroepitaxial Perovskite Metal-Base Transistor

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“More than Moore”¹ captures a concept for overcoming limitations in silicon electronics, by incorporating new functionalities in the constituent materials. Perovskite oxides are candidates due to their vast array of physical properties in a common structure. They also enable new electronic devices based on strongly-correlated electrons². The field effect transistor³ and its derivatives have been the principal oxide devices investigated thus far⁴⁻⁶, but another option is available in a different geometry: if the current is perpendicular to the interface, the strong internal electric fields generated at back-to-back heterojunctions can be used for oxide electronics, analogous to bipolar transistors⁷. Here we demonstrate a perovskite heteroepitaxial metal-base transistor⁸ operating at room temperature,

enabled by interface dipole engineering⁹. Analysis of many devices quantifies the evolution from hot-electron¹⁰ to permeable-base¹¹ behaviour. This device provides a platform for incorporating the exotic ground states of perovskite oxides, as well as novel electronic phases at their interfaces¹²⁻¹⁵.

The initial and still very active study of three-terminal complex oxide devices primarily uses the field effect transistor (FET)⁴. Despite successes in some oxides, the FET intrinsically suffers from the requirement of large electric fields needed to induce conductivity in many perovskites¹⁶. These high fields have been partially mitigated by the use of ferroelectric polarisation⁵ or electric double layer structures⁶. Historically, however, it is noteworthy that before the demonstration of the FET³, the first transistors were based not on electron transport parallel to the active interface, but rather perpendicular to them. The very first transistor, for example, used two Au Schottky contacts to *p*-type Ge¹⁷. This format has a natural advantage for our purposes, since the internal electric fields generated at Schottky junctions can be orders of magnitude larger than can be externally applied across a gate dielectric, and transconductance is controlled by the base current, not gate voltage.

A metal-base transistor⁸ consists of a semiconductor/metal/semiconductor trilayer, where each layer functions as the emitter, base, and collector, respectively, and

two Schottky junctions are formed. The heteroepitaxial structure studied here (Fig. 1a) consisted of a manganite metal layer between titanate semiconductors. The fundamental transport process of a metal-base transistor is parameterised by the current gain α , the ratio of the collector current I_C to that injected from the emitter I_E ¹⁸. Ideally, I_C is dominated by current transferred from the emitter, resulting in typical transistor operation as a current source with large output impedance at the collector. In practice, however, leakage current at the base-collector (BC) junction may contribute to I_C , which reduces output impedance substantially, even inhibiting transistor operation at room temperature in some cases¹⁹.

This issue appeared in the present study, as seen from the current-voltage characteristics of the BC and base-emitter (BE) junctions at 300 K (Fig. 1b). Rectifying behaviour indicates Schottky diodes are formed at both interfaces. In the active mode of the transistor, the BC diode is reverse-biased to electrically isolate the collector from the base, and the BE diode is forward biased to inject carriers. It is evident that the leakage current at the BC junction (red arrow) is as large as the injection current at the BE junction (blue triangle). As a result, no significant transconductance could be found in devices using this geometry.

To suppress this leakage current, the BC junction barrier height was raised by

atomically engineering the BC interface⁹. Prior to depositing $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ onto the $\text{Nb}:\text{SrTiO}_3$ substrate, a single unit cell of SrMnO_3 was deposited to change the termination layer at the interface, creating extra interface dipoles that increase the BC Schottky barrier height²⁰. These interface dipoles arise to screen the polar discontinuity at the interface, switching sign for the two different atomic terminations of the $\text{Nb}:\text{SrTiO}_3$. This suppressed the leakage current by more than four orders of magnitude (Fig. 1c), far below the injection current at the BE junction. For our purposes, SrMnO_3 was preferable to SrO insertion, both due to the higher reliability of controlling the interface termination, as well as preserving the height of the BE junction to maximize current transfer (SrO would expose the $\text{La}_{0.7}\text{Sr}_{0.3}\text{O}$ surface at the BE interface). Combining these interface-engineered junctions allows for successful transistor operation at 300 K (Figs. 2 and 3), the first demonstration of a manganite metal-base transistor.

Figure 2a shows a device operating as a hot-electron transistor¹⁰ (HET) in the common-base configuration, where electrons injected from the BE junction pass across the base and above the BC Schottky barrier (Fig. 2e). I_C is measured as a function of the collector voltage (V_{CB}) at different fixed values of I_E . α is small ($\sim 1.2 \times 10^{-4}$) as shown in Fig. 2b, indicating that while clear transconductance is observed, the current gain is

highly attenuated by the short hot-electron mean-free-path, consistent with the low mobility characteristic of manganites. Fig. 2c shows the same device in the common-emitter geometry, where I_C is measured as a function of the collector-emitter voltage (V_{CE}) at different fixed values of I_B . The deduced common-emitter current gain β ($\sim 1.3 \times 10^{-4}$, Fig. 2d), is consistent with the relation $\beta = \alpha / (1 - \alpha)$, confirming HET operation.

Another characteristic feature of HETs is complete electrostatic screening by the base. Because the emitter and collector are separated by the base metal, V_{CB} is fully screened and has no feedback on V_{EB} in the common-base output characteristics. As shown in Fig. 2a, this was indeed observed in the voltage feedback curve. However, the majority of the 53 devices we studied showed varying degrees of voltage feedback. As a representative example, the common-base output characteristics and voltage feedback for a transistor in this regime are shown in Fig. 3a. α significantly depends on V_{CB} , ranging from $\alpha = 0.11$ at $V_{CB} = -0.4$ V, to $\alpha = 0.53$ at $V_{CB} = +0.8$ V. These features indicate finite coupling of V_{EB} to V_{CB} , which arises despite the same in-plane transport and magnetic properties of the manganite films used as the base layer. Precipitates formed during manganite film growth could be ruled out as the origin of this coupling, since even for films with a high density of precipitates induced by detuning the plume

stoichiometry²¹, subsequent transistors did not exhibit any statistical increase in voltage feedback. Rather, dilute pinhole defects are the likely origin of this coupling. This is further supported by our electrical measurements which show a connection between emitter and collector, not base/emitter or base/collector.

To elucidate the operating mode of this transistor, temperature dependent measurements were taken between 20 K and 300 K (Fig. 3b). Here I_C is plotted as a function of V_{EB} at $V_{CB} = 0$ V, which gives the transfer characteristics. At small negative voltage, a linear relationship was observed between $\log I_C$ and V_{EB} , with increasing slope for decreasing temperature. This thermally-activated process indicates emitter-to-collector current dominated by activation over a barrier, similar to thermionic emission in a Schottky junction²². This picture is quantitatively supported by an ideality factor below 2 for all temperatures¹⁸.

The effective emitter-collector barrier can be visualised as the saddle point in the potential contour of the microscopic current path (Fig. 3e), which is characteristic of permeable-base transistors (PBT)¹¹. Current transfer in a PBT is determined by a current path controlled by the potential profile in the base. The barrier was quantified by measuring the common-base transfer curves at 10 K for a given V_{CB} varied across ± 0.6 V (Fig. 3c). The effective barrier height ($|V_{EB}|$ at the onset of I_C) decreased linearly by

applying a positive V_{CB} . This variability is a typical feature of PBTs, also causing partial screening in the base (Fig. 3a). The PBT shown in Fig. 3 has significantly higher current gain than the HET in Fig. 2, but still less than unity. By going further into the permeable-base regime, the gain is further increased. Figure 4 shows the case for a PBT with α very close to 1, for which the common-emitter current gain β is measured to be ~ 250 .

The output characteristics in Fig. 3a can be quantitatively described in a simple model. We define $\Phi(V_{EB}, V_{CB})$ as the effective barrier height with respect to the base (determining emitter-to-collector current transfer), and $\Phi_0 = \Phi(0,0)$ for the unbiased equilibrium state. The linear modulation of $\Phi(V_{EB}, V_{CB})$ by the terminal voltages (Fig. 3c), parameterised by the coupling coefficient b , gives

$$\Phi(V_{EB}, V_{CB}) = \Phi_0 - b(V_{EB} + V_{CB}). \quad (1)$$

Since the barrier current and hence I_C is determined by the difference in $\Phi(V_{EB}, V_{CB})$ and V_{EB} , I_C can be generalised as

$$I_C = f[\Phi(V_{EB}, V_{CB}) - V_{EB}] \quad (2)$$

by using a suitable function $f[]$, specified below. Combining Eqs. 1 and 2, $I_C = f[\Phi_0 - V_{mix}]$, where $V_{mix} = bV_{CB} - (1-b)V_{EB}$. By optimizing the scaling parameter $b = 0.25$, I_C in the range of $0 \text{ V} < V_{CB} < 0.5 \text{ V}$ can be collapsed onto a single

curve as a function of V_{mix} as shown in Fig. 3d. We further note that at high voltages, $I_C \propto V_{\text{mix}}^2$, indicating space charge limited current (SCLC) through the current path²³.

Now we can write the functional form for $f[]$ as

$$f[\Phi_0 - V_{\text{mix}}] = \begin{cases} I_0 \exp[-q(\Phi_0 - V_{\text{mix}})/kT] & (V_{\text{mix}} < \Phi_0) \\ A(V_{\text{mix}} - \Phi_0)^2 & (\Phi_0 < V_{\text{mix}}) \end{cases} \quad (3)$$

$$(4)$$

where I_0 is the prefactor of the exponential behaviour shown in Fig. 3b, k is the Boltzmann constant, and A is the linear coefficient of the SCLC. $\Phi_0 = 0.65$ V for this particular transistor, determined by the intercept in Fig. 3d. Thus this model based on a PBT captures the measured common-base output characteristics of the transistor with partial screening, as parameterised by b , Φ_0 , and A .

Application of the full analysis discussed above to all 53 transistors studied here showed universal scaling as given in Fig. 3d. The resultant parameters b and Φ_0 are plotted in Fig. 5a. When $b \approx 0$, namely I_C is determined by V_{EB} and unaffected by the collector, $\Phi_0 \sim 0.9$ V, the Schottky barrier height of the SrO-terminated $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3/\text{Nb}:\text{SrTiO}_3$ interface⁹. As b increases and reaches 0.5, I_C is determined purely by V_{CE} , and Φ_0 is reduced to a small value. These variations of b and Φ_0 can be seen as the independent consequences of the formation and expansion of the emitter-to-collector current path. When the current path expands, base screening is diminished, resulting in larger b and reduced Φ_0 . The two red circles in Fig. 5a

correspond to the two representative transistors shown in Figs. 2 and 3. Thus the correlation between b and Φ_0 in Fig. 5a indicates that the dispersion in transistor characteristics measured in all devices can be well described as the evolution from a HET to a PBT.

To corroborate this picture we analyse the dispersion of α , which was found to be proportional to A in Eq. 4 (Fig. 5b). In the simple SCLC model, I_C is expressed as $I_C = A(V_{\text{mix}} - \Phi_0)^2 = \frac{9S\varepsilon\mu}{8d^3}(V_{\text{mix}} - \Phi_0)^2$ where S is the cross-sectional area of the current path, ε is the permittivity, μ is the carrier mobility, and d is the length of the current path²³. Assuming ε , μ , and d to be constants, the observed dispersion in α can be attributed to the variation in S . The statistical distribution of Fig. 5 is consistent with a very low density of pinhole defects with respect to the device area. Using the simulation results of PBTs from Ref. 11, the maximal pinhole diameter when all transconductance is lost corresponds to ~ 100 nm, consistent with the depletion width in the collector. This indicates that further downscaling of these relatively large structures should shift device yield to the hot-electron regime. Recently developed manganite nanolithography techniques²⁴ could then be used to controllably tune the base permeability.

In summary, the present work demonstrates a new three-terminal device platform for perovskite oxide heterostructures, which should provide useful for

hot-electron spectroscopy of heterostructures incorporating strong electron interactions and quantum wells²⁵, as well as magnetically active junctions²⁶. In the hot-electron regime, the low current gains are far from commercial relevance as basic transistors, and they are comparable to those of metal-base spin-valve transistors²⁷. With further improvements, the epitaxial and thermodynamic compatibility of metallic, semiconducting, and other multifunctional states in perovskites may provide an avenue to overcome scattering and defects arising at conventional metal/semiconductor interfaces.

Methods

The transistor structure was based on (001)-oriented SrTiO₃/La_{0.7}Sr_{0.3}MnO₃/Nb:SrTiO₃ trilayers which were grown by pulsed laser deposition²⁸. On TiO₂-terminated²⁹ Nb:SrTiO₃ (001) substrates with a dopant concentration of 0.01 wt. %, a 20 nm thick La_{0.7}Sr_{0.3}MnO₃ base and an 80 nm thick SrTiO₃ emitter were consecutively grown at an oxygen partial pressure of 1×10^{-3} Torr. The substrate temperature and the laser fluence were 850 °C and 0.4 J/cm² for La_{0.7}Sr_{0.3}MnO₃ (and the inserted SrMnO₃ layer) and 700 °C and 0.6 J/cm² for SrTiO₃. The SrTiO₃ layer was deposited through a rectangular template mask. Grown in this manner on SrTiO₃ substrates, SrTiO₃ films are completely

insulating ($> 10 \text{ G}\Omega\text{-cm}$ by 4 probe measurement at room temperature). Al/SrTiO₃/Nb: SrTiO₃ test structures confirmed an Ohmic contact with a contact resistance of $\sim 100 \Omega$ for the dimensions used here. X-ray diffraction studies confirmed high quality epitaxial single crystal thin films which were fully strained to the substrate. Magnetisation measurements gave a Curie temperature of 350 K for the La_{0.7}Sr_{0.3}MnO₃ film, similar to that of the bulk²⁸. Atomic force microscopy exhibited surfaces with a unit cell step and terrace structure both for La_{0.7}Sr_{0.3}MnO₃ and SrTiO₃ films. The areas of the BE and BC junctions were 0.1 mm^2 and 0.3 mm^2 . Aluminium and gold electrodes were deposited through shadow masks on the emitter and the base respectively, and indium was contacted by ultrasonic soldering to the collector (substrate). These provide Ohmic contacts with resistances far below the junction impedances in all measurement conditions.

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Author Contributions T.Y. performed device fabrication, measurements, and data analysis. Y.H. and H.Y.H. assisted with the planning, measurements, and analysis of the study.

Competing interests statement The authors declare that they have no competing financial interests.

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Figure Captions:

Figure 1 | Device fabrication and interface engineering. **a**, A schematic illustration of the metal-base transistor with the structure of (001)-oriented SrTiO₃(STO)/La_{0.7}Sr_{0.3}MnO₃(LSMO)/Nb:STO. **b**, **c**, Current-voltage characteristics of the base-collector (BC) and the base-emitter (BE) junctions shown for devices without (**b**) and with (**c**) the insertion of a single unit cell of SrMnO₃ at the BC interface. Insets show the measurement configuration, and the arrows and triangles indicate typical voltages applied to the junctions during transistor operation.

Figure 2 | Hot-electron transistor (HET) characteristics at 300 K. **a**, Common-base output characteristics and voltage feedback, as I_E is varied from 0 to 1 μA in 0.2 μA steps. **b**, Common-base transfer characteristics for $V_{CB} = 0$ V. **c**, Common-emitter output characteristics, as I_B is varied from 0 to 1 μA in 0.2 μA steps. **d**, Common-emitter transfer characteristics for $V_{CE} = 1.4$ V. The common-base current gain α and the common-emitter current gain β are calculated from the slopes of the plots in **b** and **d**. **e**, Schematic illustration of the HET.

Figure 3 | Permeable base transistor (PBT) characteristics. **a**, Common-base output characteristics and voltage feedback at 300 K, as I_E is varied from 0 to 1 μA in 0.2 μA steps. **b**, **c**, Temperature dependence (**b**, 20 K intervals, $V_{CB} = 0$ V) and V_{CB} dependence (**c**, 0.2 V intervals, 10 K) of the common-base transfer characteristics. **d**, Scaling plot of the square root of the collector current (I_C) as a function of V_{mix} , for the optimum scaling parameter $b = 0.25$. The intercept gives the unbiased effective barrier height, $\Phi_0 = 0.65$ V. **e**, Schematic illustration of the PBT.

Figure 4 | Permeable base transistor (PBT) in the high gain regime ($\alpha \sim 1$). **a**, Common-base output characteristics and voltage feedback at 300 K, as I_E is varied from 0 to 1 μA in 0.2 μA steps. **b**, Common-emitter current transfer characteristics I_C versus I_B (at $V_{CE} = 1.4$ V), for which $\beta \sim 250$ for $I_C \sim 0$.

Figure 5 | Evolution of transistor operation. **a**, Correlation between the unbiased effective barrier height (Φ_0) and the voltage transfer between the emitter and the collector (b). **b**, Correlation between the linear coefficient in SCLC (A) and the current gain (α). In **a** and **b**, the distribution of transistor characteristics at 300 K for all 53

measured transistors are given. The dashed curves and line are guides to the eye. **c, d,**

Schematic illustrations of the current transfer for the HET and the PBT.

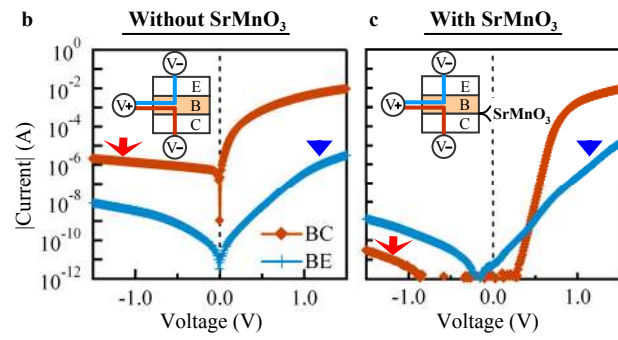
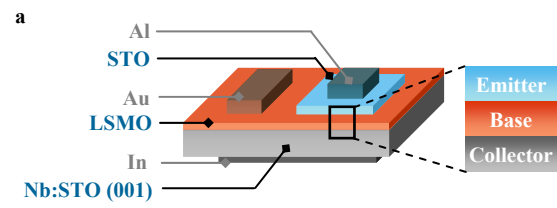


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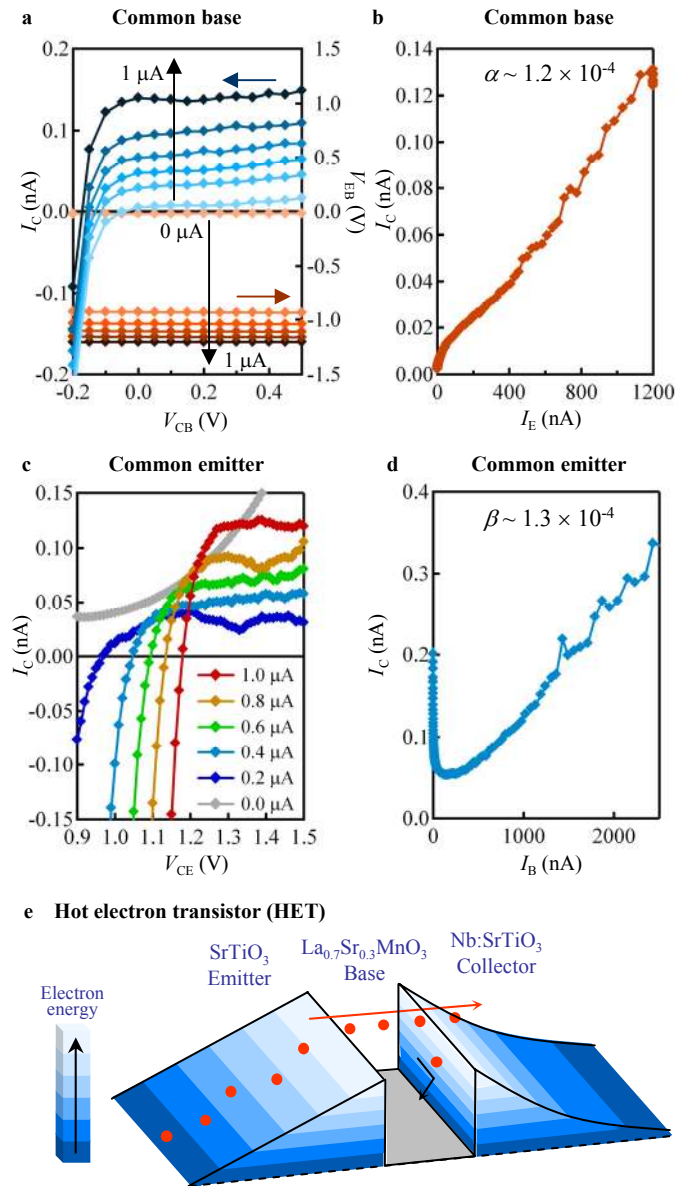
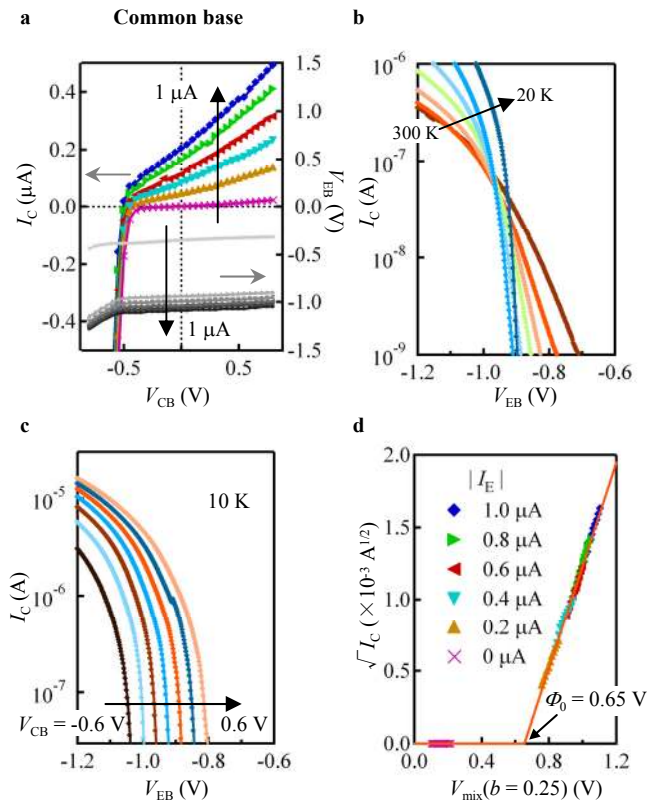


Figure 2 T. Yajima *et al.*



e Permeable base transistor (PBT)

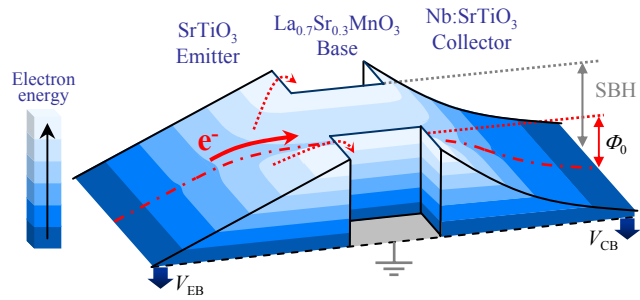


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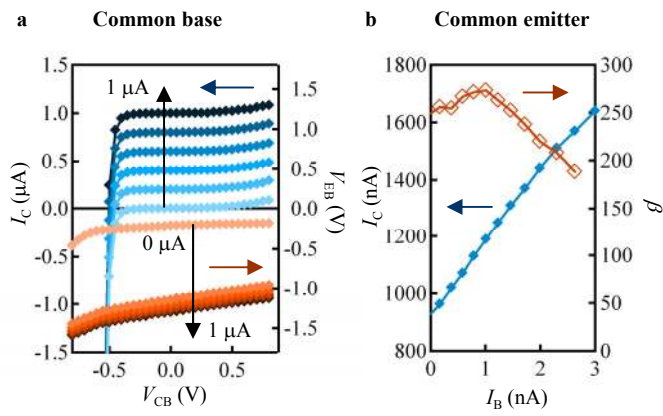


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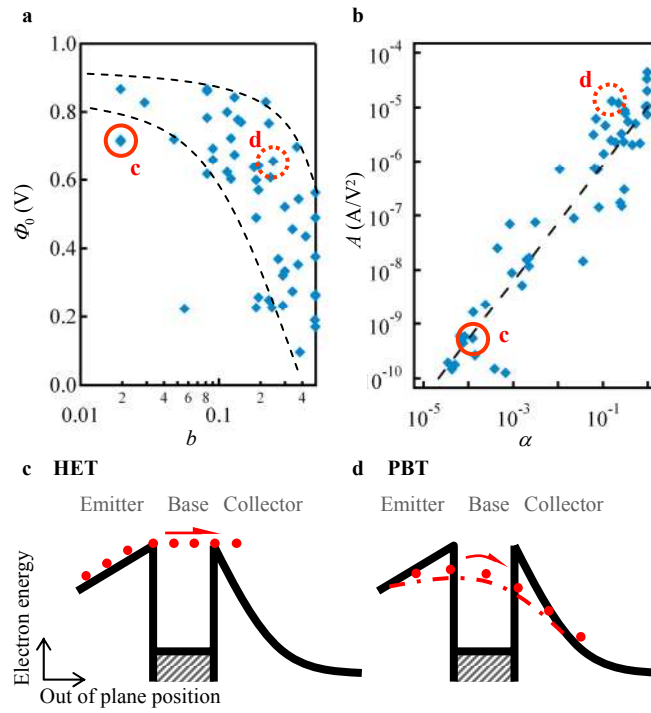


Figure 5 T. Yajima *et al.*