There were many flares here, all smaller than those near F, where fields were twice as strong. The channel structure formed in half a day and lasted for several days.

These magnetograms show the field at the intersection of a three-dimensional cluster of bipolar loops with the surface of optical depth unity (the photosphere), where the spectrum line measured originates. When we image the Sun in a much stronger line, such as Hα, we see the overlying chromosphere, where flares occur in magnetic configurations determined by the photospheric fields. The Hα structure shows fibrils parallel to the transverse fields; by matching these to the polarities in the magnetograms, we can remove the 180° ambiguity in transverse field direction. Our notion of the resulting three-dimensional field structure is sketched in Fig. 4, which shows the field line configuration generated by a moving spot. Each dipole is a horizontal slice of a flux loop, so as these loops break the surface, the poles separate at about 1 km s^{-1}. Because the field lines are stuck to the original poles, they are elongated by the motion and a sharp turn at the neutral (or inversion) line results.

If all flux loops rose at the same rate, there would only be self-similar growth and no relative motion or stress or shear on the field lines. More often a main spot emerges and new dipoles emerge later at different rates. Each flux loop expands into the older fields, but also reconnects with them[3], and field lines stretch along the expansion track of the new spots. The flux loops are thought to rise because of magnetic buoyancy, the tendency of enclosed flux loops to expand outward and rise by buoyancy[4,5], which pushes new field lines up through old. Such developments are typical of the most frequent and intense activity. Each additional channel represents a corresponding increase in the strong field-aligned currents which give rise to flares. When flux emergence ceases, the activity dies out.

These observations provide unequivocal evidence of narrow lanes of transverse field in flaring regions. Hints of such lanes appear in direct images and longitudinal magnetograms taken in 1988[5]. We are sure that the present high-resolution vector magnetograph would have shown similar field structure in those cases.

Because the field energy is the volume integral of $\mathbf{B}^2$, the

FIG. 4 Schematic diagram of the field line configuration produced by an elongated spot of negative polarity moving (arrow) between two positive spots, such as area 5 in Fig. 2a. The lines are vertical over the spots (red in 2a), then turn sharply parallel to the neutral line (green channel), and dive back to the surface at the next spots (red). In the absence of a current, the field lines would simply arch across the channel to the nearest opposite polarity.

appearance of several channels in a single boundary does not affect the energy, but each reversal produces an additional current. If the field reverses in 1,000 km, as observed, the field-aligned current density ($\nabla \times \mathbf{B}$) along a cylindrical channel would be 0.5 A m^{-2}, an order of magnitude larger than derived from lower-resolution observations[6]. The total current of each channel is 5×10^{11} A.

Because solar flares occur where magnetic shear (defined as the difference between observed and potential field configurations) is large, we assume that they release magnetic energy. Paradoxically, recent data for five flares[7,8] show that shear increases. However, indirect methods[9,10] suggest that shear decreases, which one might expect intuitively. Whatever really happens, we have shown that the flare-related magnetic fields are far more complex and convoluted than previously thought. □

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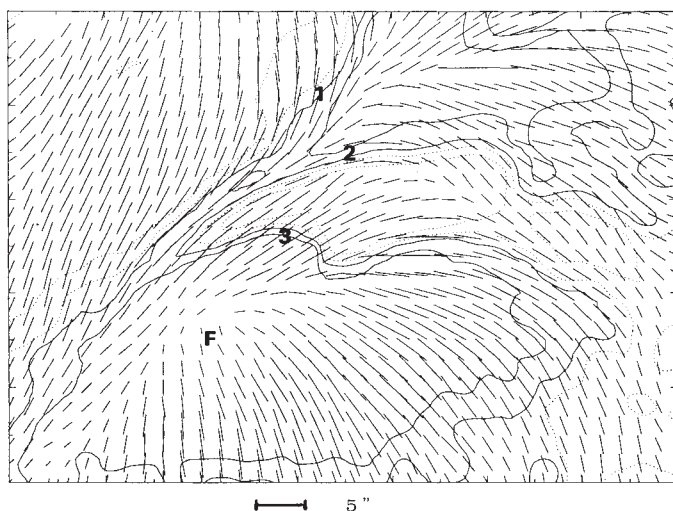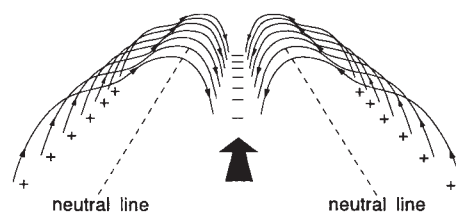10. Neidig, D. Solar Phys. 61, 121 (1979).

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FIG. 3 Magnified vector magnetogram corresponding to Fig. 1a, showing the channel structure 1–2–3 on 7 June. Solid contours are for positive, dotted for negative longitudinal field. The bars give the transverse field direction (±180°) and strength for 3 × 3 pixels at their centre. Except for the left part of channel 3, the bars run parallel to the channels. We find this alignment in virtually all δ spots. The apparent strong transverse field at lower right is the limbward projection of the longitudinal field.

Implications of the high D/H ratio for the sources of water in Venus' atmosphere

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THE high abundance ratio of deuterium to hydrogen in the atmosphere of Venus (120 times that on Earth) can be interpreted either as the signature of a lost primordial ocean[1], or of a steady state in which water is continuously supplied to the surface of Venus by comets or volcanic outgassing, balancing loss through hydrogen escape[2,3]. New observations[4-6] of a water concentration of only 30 parts per million in Venus' atmosphere imply that the residence time of water in the atmosphere, before it escapes to space, is short compared with the age of the Solar System, casting doubt on the primordial ocean hypothesis. But a recent theoretical reanalysis of collisional ejection[7] has increased estimates of

the deuterium escape efficiency by a factor of 10: this means that if the venusian water budget is in steady state, the D/H ratio of the source water must be 10–15 times higher than that on Earth, ruling out cometary water, whose D/H ratio is thought to be lower than this[8]. Here I suggest that these observations can be understood either as the result of continuous outgassing from a highly fractionated mantle source (such as might result from severe dessication of the mantle, or massive hydrogen escape early in the planet's history) or Rayleigh fractionation after massive outgassing from catastrophic resurfacing of the planet in the past 0.5–1 Gyr.

Estimates of the total escape flux of hydrogen from Venus cover a range from 0.4×10^7 to 3.7×10^7 cm^{-2} s^{-1} (refs 9–14). These fluxes are highly uncertain as they depend on the temperature structure of the nightside ionosphere and on the response of the atmosphere to changes in the solar wind, both of which are poorly known. Because the combined uncertainties in these estimates are greater than the differences among them, and because they are likely to change further as theory and observations advance, I will use this range of estimated fluxes as an indicator of the uncertainty and take a median escape flux of 2×10^7 cm^{-2} s^{-1} as a nominal value for evolutionary modelling.

Several processes contribute to hydrogen escape, each with a different efficiency of deuterium escape relative to hydrogen, represented by the fractionation factor

$$f = \frac{(dD/dt)/D}{(dH/dt)/H} \qquad (1)$$

where D and H are the atmospheric abundances of deuterium and hydrogen. Recently Gurwell and Yung[7] have reanalysed the collisional ejection of H and D. This process, the second most important escape process for H, was previously thought to be extremely inefficient at allowing D to escape, but is now found to be its main escape mechanism. (For H, the most important process is charge exchange with high-temperature ions, then collisions with fast O atoms then direct ion escape in the plasma tail.) They find a weighted fractionation factor, averaged over the three important escape processes, of $f = 0.13$, an order of magnitude higher than previous estimates.

A new spectroscopic analysis of the near-infrared windows on the nightside of Venus yields a water abundance of 30 ± 10 p.p.m. (refs 4, 5). Previous spacecraft measurements had left an order-of-magnitude uncertainty in the water abundance, estimated at 20–200 p.p.m. (refs 1, 14–16). The Pioneer Venus large-probe neutral mass spectrometer data, originally interpreted to give a substantially greater water abundance[16], have been re-analysed[6] to yield 28 p.p.m., in agreement with the new spectroscopic determinations. A consensus thus seems to have emerged on the present abundance of water on Venus. This remarkably desiccated atmosphere has a lifetime against H escape of 74 million to 680 million years, for the escape fluxes given above. Even the high end of this range is much shorter than the age of the Solar System. This suggests that water on Venus now is probably not the remnant of a large ancient reservoir. With these relatively short lifetimes, more recent sources are probable and a steady state is more likely.

The time-dependent solution for evolution of D/H in an atmosphere with a steady-state water abundance is given by[2,17]

$$\left(\frac{D}{H}\right)(t) = \frac{\alpha}{f} - \left[\frac{\alpha}{f} - \left(\frac{D}{H}\right)_0\right] \exp\left(-\phi ft/H_{ss}\right) \qquad (2)$$

where H_{ss} is the steady-state hydrogen column abundance, α is the D/H ratio in the source, ϕ is the flux of H through the system in cm^{-2} s^{-1}, and $(D/H)_0$ is the D/H ratio at time $t = 0$. Here the time-dependent term represents the signature of the original D/H ratio which decays asymptotically with time constant

$$\tau_{ss} = \frac{H_{ss}}{\phi f} = \tau_{H_2O}/f \qquad (3)$$

After a steady state has existed for several times τ_{ss}, the D/H

ratio decays towards the steady-state limit, $(D/H)_{lim} = \alpha/f$. I will refer to this limiting state as a 'mature steady state'. This time constant is longer than the lifetime of water by a factor of $1/f$, as indicated by equation (3), so that water reaches steady state well before the D/H ratio reaches the limiting value. The behaviour of equation (2) for a range of parameters is shown in Fig. 1. Only after several times τ_{ss} does the system achieve a mature steady state, with the D/H ratio relaxing towards $(D/H)_{lim}$.

The theoretical work described above raises the weighted fractionation factor by an order of magnitude over the value used in earlier evolutionary modelling[2,14]. As both $(D/H)_{lim}$ and τ_{ss} vary inversely with f, this change has a paradoxical effect on the interpretation of the significance of the observed D/H ratio for the history of water on Venus. Assuming that the source hydrogen has a terrestrial D/H value ($\alpha = 1.6 \times 10^{-4}$), then the higher value of f gives $(D/H)_{lim} = 1.23 \times 10^{-3}$, well below the observed value for the steady-state limit D/H ratio. The nominal value of τ_{ss} is now reduced to 1.1×10^9 years. Thus we have a paradox: the timescale is now more favourable for the system to have reached $(D/H)_{lim}$ in several billion years ($\tau_{ss} <$ age of
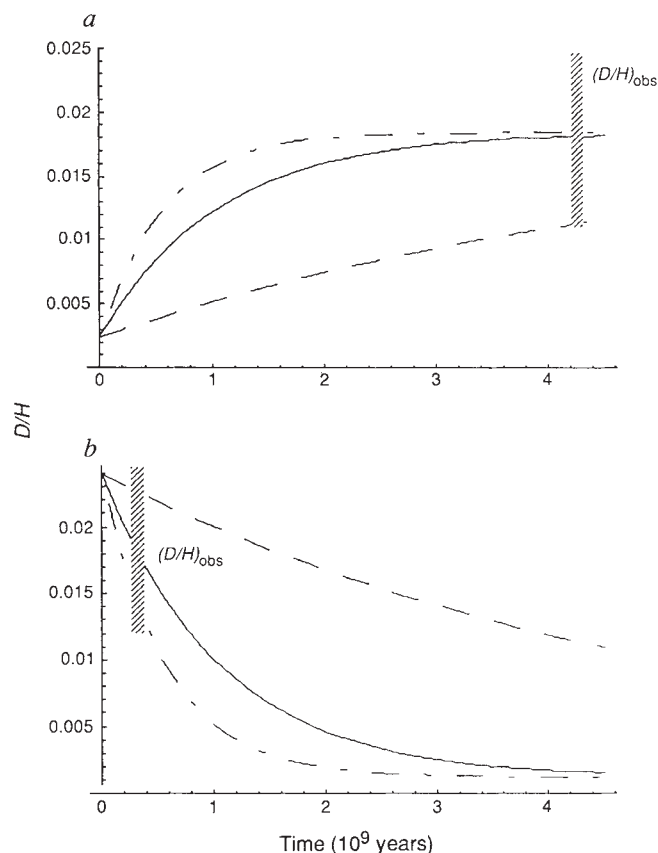

FIG. 1 Hypothetical curves of the evolution of the deuterium/hydrogen ratio with water in steady state, from equation (2) using $f = 0.13$. Solid, dashed and dot-dash curves are for H escape fluxes of 2.0, 0.4 and 3.7×10^7 cm^{-2} s^{-1}, respectively. These curves show that in steady state, the ratio will eventually converge towards $(D/H)_{lim}$, with the timescale depending on the H flux. Observed ratio shown is 120 ± 40 times the terrestrial value[28]. a, Curves for $\alpha = (D/H)_0 = 15$ times terrestrial, showing that for a H source with an enhancement of this order, steady state can produce the observed D/H. b, α = terrestrial, and $(D/H)_0 = 150$ times terrestrial, the value calculated in the text for fractionation following catastrophic resurfacing. This curve shows that an enhanced D/H created by Rayleigh fractionation from massive escape would be preserved if this episode occurred in the last 10^9 years, but might well be erased if the episode of fractionating escape was 'primordial'.

Venus), yet the limit has now decreased to well below the observed value $((D/H)_{lim} < (D/H)_{obs})$.

Possible explanations for this dilemma fall into two categories, each with implications for the evolution of Venus. One possibility is that water on Venus is in steady state, with some source (such as volcanic outgassing) balancing hydrogen loss to space. In this case the D/H ratio of the source hydrogen (α) must be substantially higher than that of terrestrial water. A value of α enhanced by a factor of 10 or 15 over the terrestrial value would result in $(D/H)_{lim} \approx (D/H)_{obs}$ (Fig. 1a). This would preclude comets from being the dominant source of water if the observations of D/H for comet Halley[8] are representative.

If the atmosphere is in steady state with an outgassing source, then the H escape flux provides a direct measure of the time-averaged outgassing flux of hydrogen-containing gases over the last $\tau_{H_2O} \approx 130$ million years. An H escape flux of $\sim 2.0 \times 10^7$ cm^{-2} s^{-1} gives an upper limit for the outgassing flux of 4.3×10^{10} g of water per year. This estimate may be combined with recent observations by the Magellan spacecraft to evaluate the nature of outgassing and the likelihood of steady state with a fractionated mantle source.

Magellan mapping of volcanic features[18], combined with simulations of the crater population[19-21], has allowed preliminary estimates for volcanic resurfacing rates of ~ 0.4 km^3 yr^{-1} (ref. 21), yielding a rate of magma production of $\sim 1.2 \times 10^{15}$ g yr^{-1}. Combining this with the outgassing flux yields a lower limit for the average water content of venusian magmas of ~ 50 p.p.m. by weight, assuming efficient outgassing of lava flows. This is more than 1,000 times drier than typical basaltic magmas on Earth[22]. Even if outgassing is inefficient, venusian magmas are apparently extremely desiccated, perhaps implying a desiccated mantle. A desiccated mantle could be the result of a history of outgassing with no recycling of water in the absence of a surface reservoir and only limited subduction. Could this mantle reservoir be the source of the fractionated hydrogen necessary to reconcile $(D/H)_{obs}$ with $(D/H)_{lim}$? The D/H fractionation factor for mantle degassing has not been modelled, and is probably near unity. Large fractionation effects are found, however, in severely depleted reservoirs. If water in the mantle has been depleted by a factor of 10^5 (roughly the difference between the known water reservoirs of Venus and Earth), then an outgassing fractionation factor of $f = 0.8$ could have enhanced D/H in the mantle by a factor of 10. Alternatively, an enhanced mantle ratio could reflect massive hydrogen escape which occurred very early in the planet's history and was frozen into the mantle when an early magma ocean solidified. If so, the observed D/H may be the result of primordial water loss, but this signature would have been preserved in the mantle, not in the atmosphere.

Another possibility is that there has been a massive injection of unfractionated water within the past 0.5–1 billion years followed by massive fractionating escape. If this occurred less than several times τ_{ss} ago, then the enhanced D/H from this episode would be preserved whether or not venusian water is currently in steady state. It may be relevant that the cratering record of Venus (as revealed by Magellan) is peculiar in that the surface is young (compared with other non-terrestrial surfaces in the inner Solar System) and yet there is little evidence of any ongoing processes which are rapidly removing craters. This has led to the hypothesis that a catastrophic resurfacing occurred 0.5–1 Gyr ago, covering up all earlier craters[20]. This idea, still controversial, has received support from Monte Carlo models of surface evolution[21], and from geochemical and thermal models[23,24] which suggest that the interior may go through periods of episodic overturn with a frequency of ~ 0.5 Gyr. Alternatively, the interior and surface may simply have been continuously more active before that time.

Much higher resurfacing rates in the relatively recent past would have important consequences for atmospheric and climatic evolution. The volcanic gases SO_2 and H_2O are the chief contributors to the strong atmospheric greenhouse[25]. Catastrophic resurfacing would greatly increase the outgassing rates and thus the abundances of these gases, until escape processes, photochemistry and surface reactions returned abundances to their equilibrium values. The volume of magma necessary to resurface the planet deeply enough to cover all pre-existing craters is approximately 5×10^9 km^3 (ref. 23). Scaling the current estimated resurfacing rate and hydrogen escape flux, this episode, which is estimated to have occurred over a period of 10^7–10^8 years[23], could have injected up to ~ 150 times the current water inventory, or 4,500 p.p.m. water, into the atmosphere. The fractionation factor and timescale for the ensuing rapid hydrogen escape would depend on which escape processes dominated. Diffusion-limited escape could remove this much water on a timescale of several hundred million years, but the expected escape processes and rates for a venusian atmosphere with greatly increased water abundances are only partially understood[26,27]. The isotopic effects of this rapid escape are best modelled as a Rayleigh fractionation[1,2]

$$\left(\frac{D}{H}\right)_1 = \left(\frac{D}{H}\right)_0 \left[(X_{H2O})_0 / (X_{H2O})_1\right]^{1-f} \qquad (4)$$

where X_{H2O} is the mixing ratio of water, is assumed to represent the total hydrogen inventory and the subscripts 1 and 0 indicate the values at present, and at the start of the fractionating escape, respectively. Escape of 150 times the current water inventory, with the fractionation factor of 0.13 estimated for the current atmosphere, would enhance the D/H ratio by a factor of ~ 80. The uncertainty in this estimate is at least a factor of several hundred per cent, but it demonstrates that a recent massive outgassing event (or very massive comet impact(s)) could cause an enhancement of the D/H ratio of the order observed. Thus $(D/H)_{obs}$ may be the isotopic signature of catastrophic resurfacing in the past 0.5–1 Gyr.

This interpretation requires no current hydrogen source. After the massive injection of water, escape processes would decrease the water abundance, with a concurrent increase in D/H due to Rayleigh fractionation, until the escape flux declined to a rate equal to the hydrogen source flux (equal to the time-averaged flux of cometary hydrogen plus any outgassing contribution). It is not possible with current observational uncertainties to determine whether water is at present declining or in steady state. After the system returned to steady state, the enhanced D/H ratio would decline asymptotically towards $(D/H)_{lim}$, as seen in Fig. 1b. This figure demonstrates that if a steady state exists it could not have greatly affected the D/H ratio in the time since the hypothesized catastrophic resurfacing. Figure 1b also shows that $(D/H)_{obs}$ is probably not the signature of primordial water escape, which would have disappeared by now. In contrast, the timescale for the hypothesized catastrophic resurfacing is consistent with τ_{ss}.

Alternatively, if the actual hydrogen escape flux is lower than current theory suggests, τ_{ss} could be sufficiently long that the atmosphere would not approach $(D/H)_{lim}$ over the age of the planet. In this case $(D/H)_{obs}$ could be the remnant of a period of massive fractionating escape early in the planet's history, yet the relationship between $(D/H)_{obs}$ and the 'primordial' water inventory would be difficult to determine. The extremely dry atmosphere seems to preclude this possibility. The mass of water corresponding to a mixing ratio of 30 p.p.m. is roughly 10 times the water content of comet Halley. Even without any outgassing source over the history of the planet, primordial water may have been replaced many times over by comet impacts and subsequent escape. For more certain assessment of the alternatives, we need more detailed models of escape mechanisms and the response of the atmosphere to large water abundances. □

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Nanometre-scale recording and erasing with the scanning tunnelling microscope

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DATA storage on magnetic and optical disks and in semiconducting devices is being achieved at ever higher areal densities[1,2]. The use of the scanning tunnelling microscope (STM) for both data storage and nanofabrication has been explored recently[3–9]. These approaches use the STM tip to produce nanometre-scale marks or structures on a surface, sometimes with atomic precision. Most studies have, however, neglected erasure of recorded marks (an exception is described in ref. 10), despite the fact that erasure is essential for any practical recording device. Here we demonstrate the use of the STM for reproducible and reversible recording and erasing of marks about 10 nm in size. These are written at ambient temperature and pressure onto the surface of a composite medium consisting of a thin layer of a vanadate glass deposited on vanadium bronze, β-Na$_x$V$_2$O$_5$. The present recording speed of 1 ms is several orders of magnitude too slow for practical applications; this remains a challenge for future study.

Using single atoms as the memory units in a data storage device is an ultimate goal of attempts to manipulate atoms with the STM and atomic force microscope (AFM). But manipulation of atoms requires ultra-high vacuum, low temperatures and long times[3]. Moreover, reversibility is one of the most important factors for data storage devices. In those approaches that involve changes in surface topography — for example, where the local tip pressure of the AFM creates a mark[5] — the mark is impossible to erase. In addition, it becomes hard to distinguish between recording marks and pre-existing surface defects, especially in smaller marks. Nanometre-scale chemical modification, using STM and compounds of composition Ag$_x$Se, has

been reported[6], but again erasure is prohibited because the selenium atoms are removed from the surface of the medium by reaction with ambient hydrogen.

Basing recording and reproduction on changes in tunnelling current without any change in surface morphology seems a more suitable way to produce an STM memory. It is well known that phase transitions, for example from amorphous to crystalline, change electrical properties. If a phase change can be induced locally and in a controlled manner by using an STM, it might be possible to achieve all of the necessary storage functions by modifying the tunnelling current.

Chalcogen compounds and vanadate glasses, which show a phase transition accompanied by electrical conductivity changes, were examined as possible recording media. Both materials proved inadequate, however, because of chemical instability for the former and irreversibility for the latter. We finally adopted as a potential recording medium a composite material comprising a crystalline vanadate and its glassy, amorphous form[11].

The glass was prepared by rapid quenching[11]. The glass composition obtained was 14 mol% Na$_2$O–71 mol% V$_2$O$_5$–15 mol% P$_2$O$_5$. The V$_2$O$_5$ is an electrical conduction component. Crystal phase stability and the mechanism of electrical conduction depend on the Na$_2$O concentration. The P$_2$O$_5$ was added to stabilize the amorphous form. The glass was heat-treated at 573 K for 1 hour to crystallize it. Deposited crystals were identified as β-Na$_x$V$_2$O$_5$, $x \approx 0.33$ ('vanadium bronze') by X-ray diffraction. The vanadium bronze possesses unique electrical properties, including quasi-one-dimensional conduction and small polaron behaviour[12,13]. The amorphous phase in the crystallized glass can be classified into two states. One is a heterogeneous phase, more than 100 nm thick. The other is a uniform layer less than 10 nm thick on the bc-plane of the vanadium bronze crystal. The latter was suitable for a reversible recording and erasing medium.

Figure 1A shows a 100×100 nm^2 top-view STM image after four marks have been recorded. The bias voltage for imaging was +0.7 V. The mark size was about 10×10 nm^2, corresponding to $\sim 1 \times 10^{12}$ bits per square inch area density. This recording was made on 10-nm-thick amorphous material on the bc-plane of β-Na$_x$V$_2$O$_5$. The marks were formed by applying pulsed voltages of +4 V (the bias polarity refers to the sample) for times of (a) 10 ms, (b) 5 ms, (c) 2 ms and (d) 1 ms. The instantaneous tunnelling current during a pulse of +4 V lasting for 1 ms is about 50 nA. For data storage a recording speed of 1 ms is orders of magnitude too slow. We hope that higher recording speeds might be attained by using as the recording medium materials in which the ion mobility is greater. These can range over several orders of magnitude; for example, the ion conductivity for superionic conducting glass, such as the AgI–Ag$_2$O–P$_2$O$_5$ system[14], can be more than four orders of magnitude higher than for the vanadate glass.

Marks were erased by applying a reverse-polarity pulse of −5 V for 10 ms, as shown in Fig. 1B. This reversible transforma-
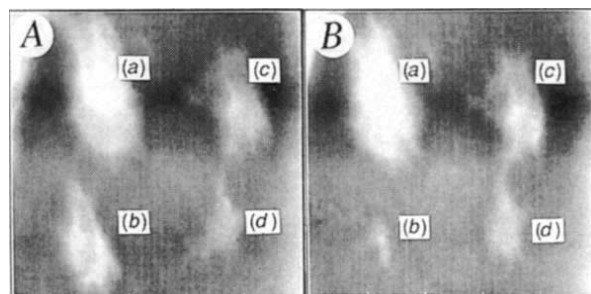

FIG. 1 A, Top-view STM image after recording four marks. The marks were recorded using pulses of 4 V for (a) 10 ms, (b) 5 ms, (c) 2 ms and (d) 1 ms. B, The STM image after applying a reverse-polarity voltage pulse (−5 V for 10 ms) to mark (b).