Low Temperature Annealing of Superconducting Bismuth Nickel Bilayers

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Abstract

This work shows bismuth nickel bilayers will anneal at room temperature over a period of 2 weeks, increasing the superconducting T_C of the sample until it has saturated to 3.8 k. During annealing bismuth atoms diffuses across the interface forming a $NiBi_3$ alloy which has a similar T_C of 4.1 k. The activation energy for this annealing is (0.86 ± 0.06) eV and it is also observed that heating at temperatures as little as 50° C for 1 hour is enough to cause a significant increase in the T_C. This aging process poses a challenge to studying distinct Bi/Ni bilayers as any slight heating will degrade the interface.

Introduction

- Superconductivity was initially noticed in bismuth growth on a nickel dusting in 1990 after which not much happen until recently [1]
- The recent interest is the potential for unusual superconductivity at the interface. Given the close proximity of superconductivity, ferromagnetism and strong spin orbit coupling there are several proposed origins:
  1. p-wave superconductivity [2]
  2. Non-trivial topology [3]
  3. Spontaneous formation of $NiBi_3$ alloy during growth process [4]
- Since bismuth has a low melting point it is important to look at what temperatures and timescales diffusion across the interface is significant. Also if this diffusion forms the superconducting $NiBi_3$ alloy
- With $NiBi_3$ at the interface it would not exclude some of the other possibilities but it is important to take into consideration this annealing process

Conclusion

- Bismuth nickel interfaces will anneal at low temperates increasing the superconducting T_C, to properly study clean interfaces samples must be kept cold at all stages
- Similarities in T_C, H_{C2} and x-ray crystallography identifies $NiBi_3$ as the origin of the superconductivity after forming by annealing
- A large effective superconducting thickness and the expected thin $NiBi_3$ layer indicate proximity effect in the bismuth layer
- Even with $NiBi_3$ at the interface the results here and elsewhere show that it is unlikely to be a typical type-II superconductor

References

[1] J. S. Moodera and R. Meservey. *Phys. Rev. B*, 42:179–183, 1990.

[2] G. Xin-Xin *et al. Chinese Phys. Lett.*, 32(6):067402, 2015.

[3] G. Xin-Xin *et al. Sci. Adv.*, 3(3):e1602579, 2017.

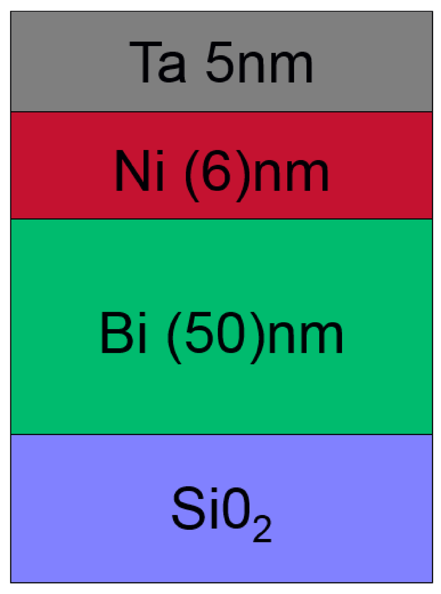
[4] V. Siva *et al. J. App. Phys.*, 117:083902, 2015.

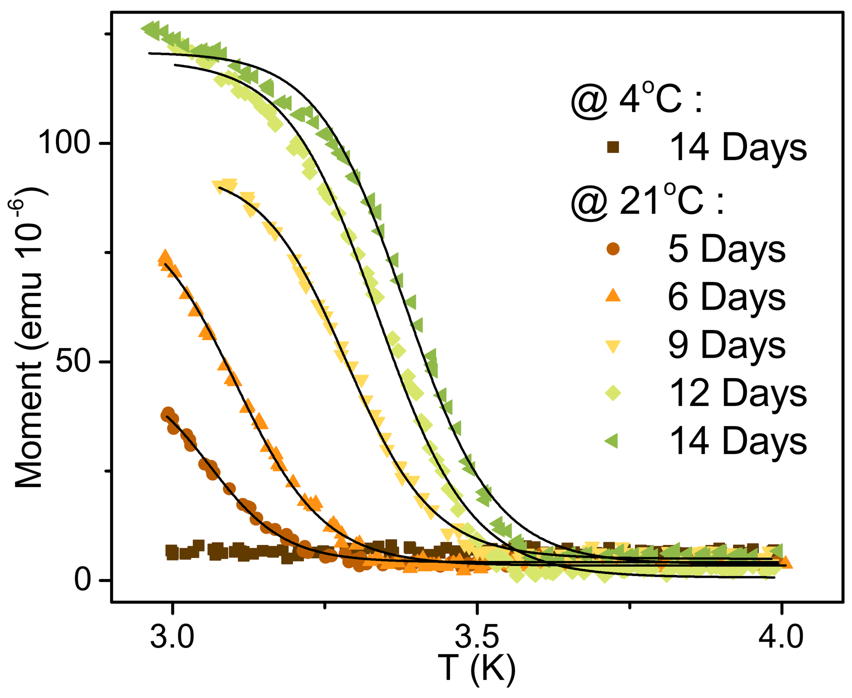
[5] H. J. Hofler *et al. J. App. Phys.*, 74(6):3832–3839, 1993.

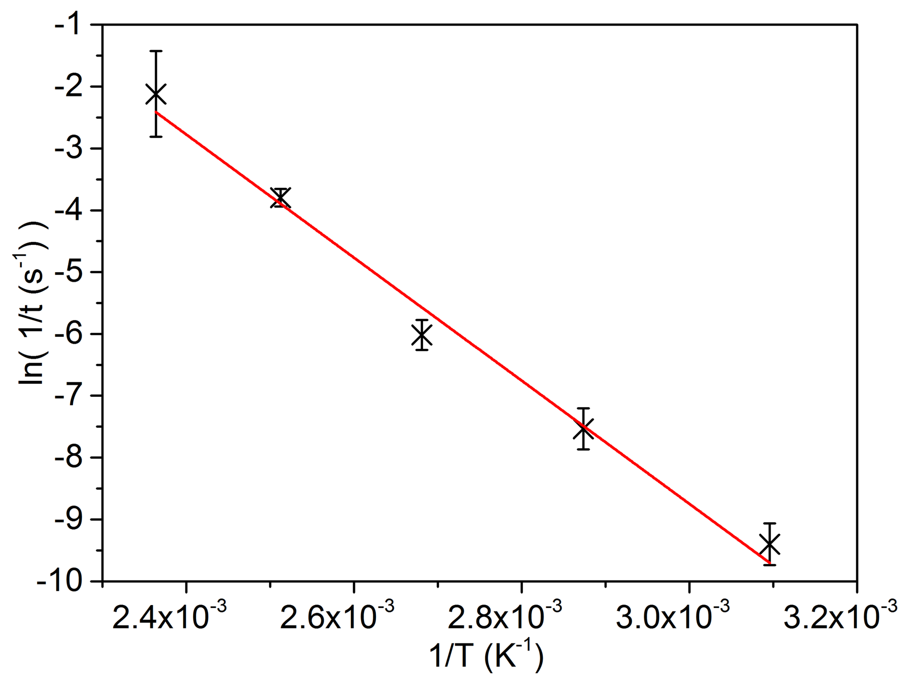
[6] E. Piaeiro *et al. Solid State Comm.*, 151(6):425 – 429, 2011.

Sample Growth and Annealing

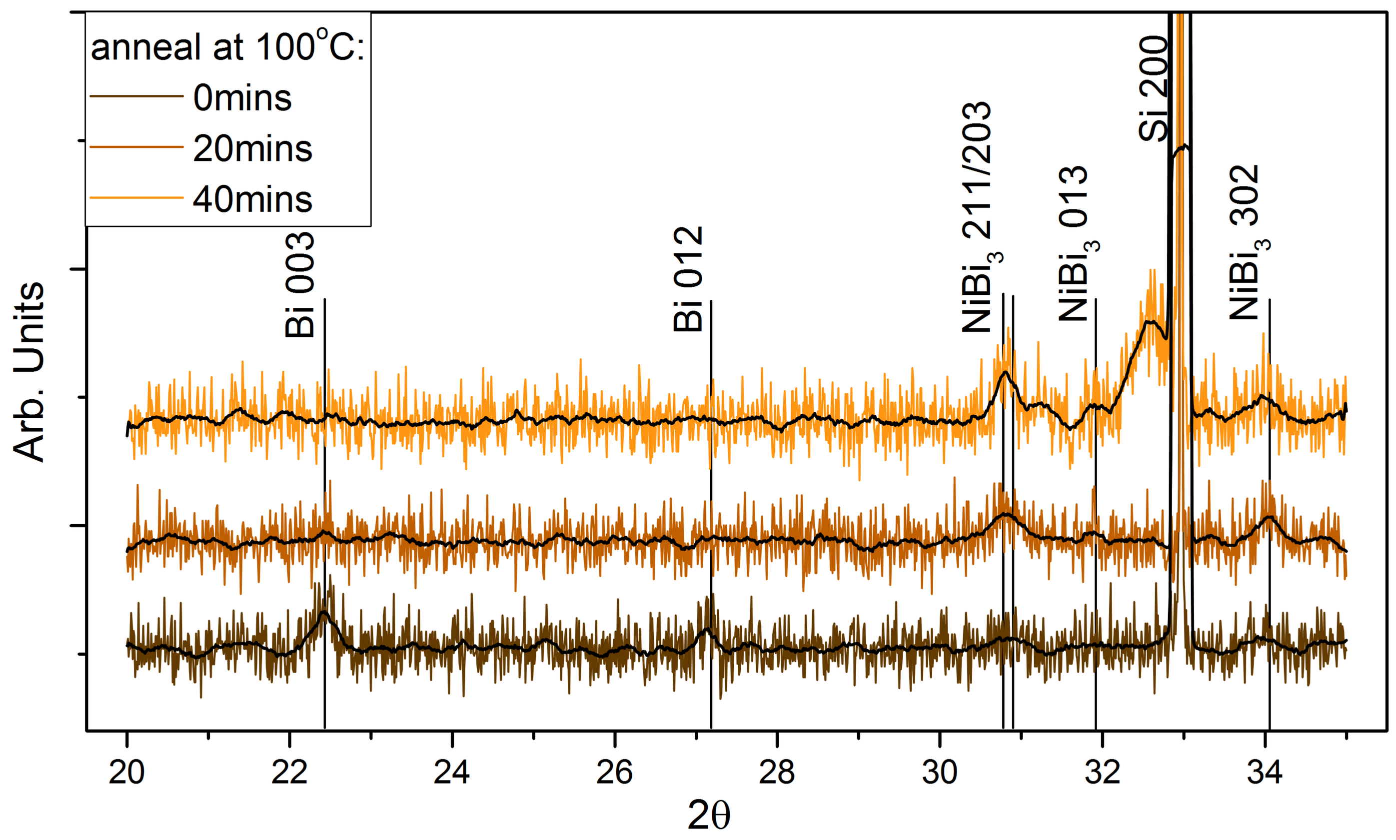
- Samples were grown by DC magnetron sputtering at 20° C and a base pressure of 9×10^{-8} torr, afterward they were stored at $\approx 4°$ C to prevent annealing
- Superconducting T_C was maximized for 50 nm of bismuth and 6 nm of nickel, 5 nm tantalum cap to prevent oxidization. Superconductivity known to be independent on growth order
- Annealing was done using a preheated hot plate with a cover for uniformity, this rapidly heated and cooled the low thermal mass samples placed on it, reducing timing uncertainty





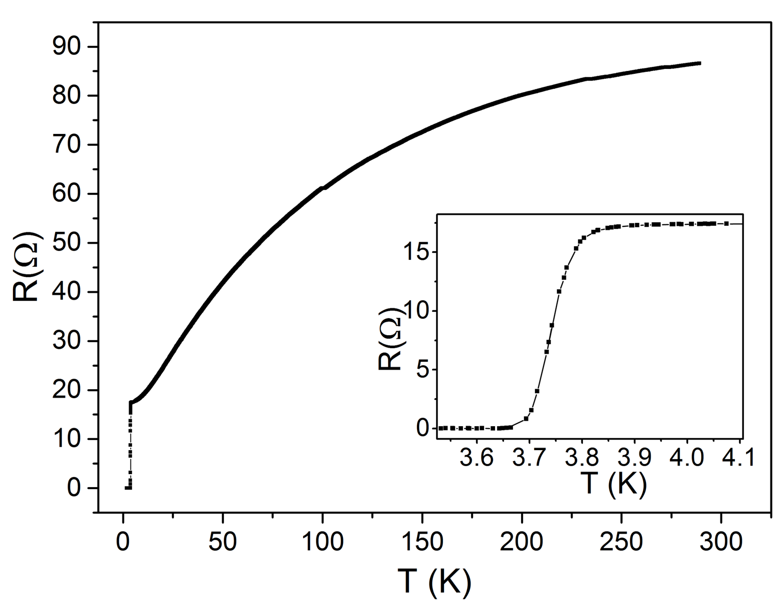


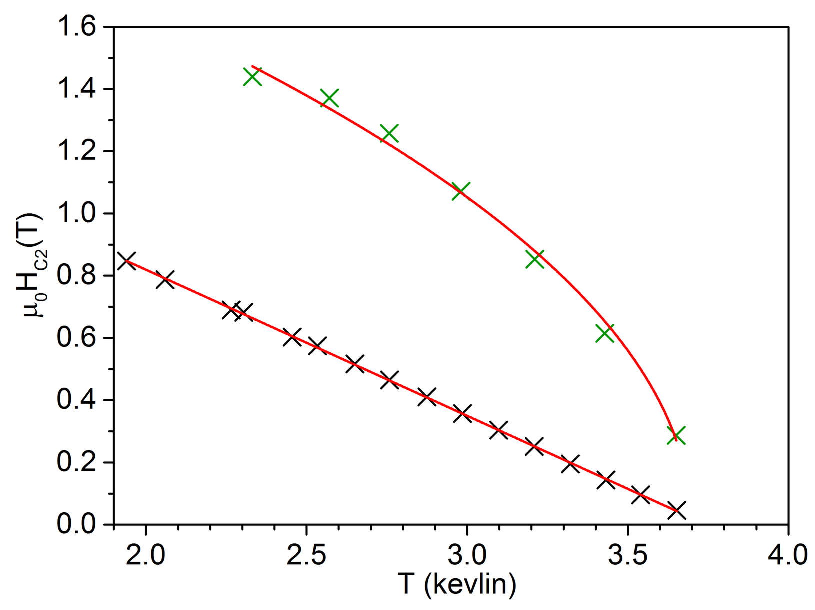
- Clear aging of the sample at $\approx 21°$ C as the onset point of the meissner effect increased over a period of 2 weeks, magnetization is measured as an absolute value, sample unchanged at $\approx 4°$ C
- The annealing rate against temperature was fitted well by the Arrhenius equation for a thermally activated reaction with an associated activation energy of (0.86 ± 0.06) eV
- The low activation energy is similar to bismuth gold interface diffusion with activation energies of ≈ 1 eV [5] and the low melting point of bismuth (271° C) explains why bismuth is so mobile and can diffuse across the interface at low temperatures



- Annealed samples showed $NiBi_3$ peaks in high angle x-ray diffraction along with the Si 200 forbidden peak
- The timescale of the appearance of these peaks was of similar timescale to the meissner onset rate which took 30 mins to saturate the T_C at 100° C
- Shoulder on the Si 200 for 40 mins annealed is substrate related and not part of the thin film

Superconductivity and Magnetic Properties





- 4-point measurements of a samples annealed at 150° C until the superconducting T_C has saturated at 3.8 k, bulk $NiBi_3$ T_C is 4.1 k
- H_{C2} temperature dependence is fitted well by the GL model for a thin superconductor with an effective superconducting thickness of 37 nm and a coherence length of 15 nm

- Since the $NiBi_3$ layer is expected to be very thin it must be proximitizing the remaining bismuth layer which is known to preserve superconductivity up to 125 nm
- Above H_{C2} exists a ferromagnetic like magnetization, the above T_C hysteresis loop (Red) has a similar saturation moment
- The coexistence of superconductivity and ferromagnetism is unusual, although is has been suggested that $NiBi_3$ is also simultaneously superconducting and ferromagnetic [6]